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Proceedings of the Workshop on Long-range, Low Frequency Acoustic Fish Detection

Compte rendu de l'atelier sur la détection acoustique des poissons à longue distance et basse fréquence

29 – 31 January 2007
Radisson Suite Hotel
Halifax, Nova Scotia

Du 29 au 31 janvier 2007
Hôtel Radisson Suite
Halifax (Nouvelle-Écosse)

Norman A. Cochrane[1]
Gary D. Melvin[2]
DFO Convenors and Proceedings Editors

[1]Bedford Institute of Oceanography (BIO)
1 Challenger Drive, P.O. Box 1006
Dartmouth, Nova Scotia
B2Y 4A2

[2]St. Andrews Biological Station (SABS)
531 Brandy Cove Road
St. Andrews, New Brunswick
E5B 2L9

Norman A. Cochrane[1]
Gary D. Melvin[2]
Facilitateurs du MPO et rédacteurs du compte rendu

[1]Institut océanographique de Bedford (IOB)
1, promenade Challenger, C.P. 1006
Dartmouth (Nouvelle-Écosse)
B2Y 4A2

[2]Station biologique de St. Andrews (SBSA)
531 Brandy Cove Road
St. Andrews (Nouveau-Brunswick)
E5B 2L9

October 2007

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Canada

Foreword

The purpose of these Proceedings is to document the activities and key discussions of the meeting. The Proceedings include research recommendations, uncertainties, and the rationale for decisions made by the meeting.

This workshop was not carried out as a formal Department of Fisheries and Oceans (DFO) Science Advisory process; however, it is being documented in the Canadian Science Advisory Secretariat (CSAS) Proceedings series as it documents an area of current technological advance directly relevant to stock assessment and fisheries research.

Avant-propos

Le présent compte rendu a pour but de documenter les activités et principales discussions qui ont eu lieu au cours de l'atelier. Il contient des recommandations sur les recherches à effectuer, traite des incertitudes et expose les motifs des décisions prises par les participants.

L'atelier dont il est question n'a pas été tenu dans le cadre officiel du processus des avis scientifiques du ministère des Pêches et des Océans (MPO), mais il fait néanmoins l'objet d'un compte rendu du Secrétariat canadien de consultation scientifique (SCCS), car il portait sur des progrès techniques d'un intérêt direct pour l'évaluation des stocks et la recherche halieutique.

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SUMMARY

A three-day workshop was held in Halifax, NS, from 29 – 31 January 2007, to explore potential applications of rapidly evolving, mainly low active sonar techniques to the long-range (multi-kilometer to tens of kilometer) detection, observation, and quantification of Department of Fisheries and Oceans (DFO) Maritimes Region fish stocks. Invited presentations from Canadian and international experts assessed the current status of the field, outstanding and possible addressable stock assessment issues in Maritimes Region, and explored in some detail issues in acoustic target properties, acoustic propagation, hardware impiementations, and possible environmental impacts.

These proceedings document the workshop presentations in summary form. Presenter-furnished abstracts and reference materials, when provided, have also been included as an additional resource. Finally, the DFO convenors have attempted to draw some overall post-workshop conclusions from the presented materials and accompanying formal workshop discussions and to make preliminary recommendations in the DFO Maritimes Region context.

SOMMAIRE

Un atelier de trois jours s'est tenu à Halifax (N.-É.) du 29 au 31 janvier 2007 dans le but d'explorer les possibilités d'appliquer à la détection, à l'observation et à la quantification à longue distance (sur des distances allant de plusieurs kilomètres à des dizaines de kilomètres) des stocks de poisson de la Région des Maritimes les techniques de sonar actif, essentiellement à basse fréquence, qui sont en rapide évolution. Des experts canadiens et internationaux invités ont à cette occasion évalué la situation actuelle dans ce domaine, examiné les problèmes de gestion des stocks de la Région des Maritimes qui restent en suspens ainsi que ceux qu'il serait possible de traiter et étudié en détail divers sujets ayant trait aux propriétés de la réflexion acoustique, à la propagation acoustique, à la mise en place de matériel et aux incidences environnementales possibles.

Le présent compte rendu décrit sommairement les exposés auxquels l'atelier a donné lieu et intègre les résumés et documents de référence soumis par les orateurs, le cas échéant. Après l'atelier, les facilitateurs du MPO se sont efforcés de tirer des conclusions générales des documents présentés et des discussions structurées qui y étaient associées, et de formuler des recommandations préliminaires dans le contexte de la Région des Maritimes.

INTRODUCTION

A Department of Fisheries and Oceans (DFO) sponsored workshop was held in Halifax, Nova Scotia (Radisson Suite Hotel), from 29 - 31 January 2007, to consider the application of mainly low frequency (LF), acoustic techniques for the long-range detection and quantification of fish. A strong impetus behind this undertaking was the recent *Science* publication[1] by Massachusetts Institute of Technology (MIT) Prof. Nicholas Makris and co-workers describing the successful use of low frequency active sonar to detect, image, and study the spatial properties of fish aggregations on the outer New Jersey Shelf at observation ranges of tens of kilometers. At about the same time, a need was identified by fisheries assessment scientists in DFO Maritimes Region to better understand the large scale spatial movements of herring onto and off spawning grounds bordering western Nova Scotia, in order to deploy and to interpret conventional acoustic assessment tools more efficiently. It was immediately clear that the above emerging sonar technology might have potential for fulfilling the identified need. Unfortunately, it was less clear what the current state of the art really was, what scale of effort and attendant resources would be required to mount an exploratory field program(s) along these lines, and whether possibilities existed for future collaborative ventures with groups actively involved in long-range sonar for fisheries or other applications. Beside the above mentioned high profile work, it was known that other groups, past and present, had demonstrated or were in the process of developing diverse acoustic techniques for fish detection with perhaps more modest range capabilities, but still significantly exceeding those routinely achieved by today's standard shipboard-based fisheries multibeams. Because of their apparent cost effectiveness and comparative ease of use, it was thought worthwhile to also investigate the potential application of several of these alternative techniques.

The primary emphasis of the workshop (Agenda: Appendix 1) was to review the current status of long-range acoustic techniques potentially applicable to identified stock assessment issues in DFO Maritime Region and to explore the wide host of technological, oceanographic, and environmental impact issues associated with their potential implementation. Toward this end, the workshop proceedings incorporates a running summary of material presented. Initially drafted summaries prepared by the DFO convenors were forwarded to individual presentation authors for their critiques and suggestions. It is hoped that the final form usefully captures the essence of the original presentations. Most presentation authors have also forwarded additional abstracts and/or reference materials. These have been included in a separate section with only minimal editing.

The DFO convenors have also been tasked with making some overall sense of the presented material and discussions and with also providing preliminary, but considered, recommendations as to resulting future research directions in DFO Maritimes Region. This has been attempted in the "Observations and Conclusions" section near the end of the workshop proceedings and should be considered separate from the workshop-originating materials. Restraint has been exercised on discussing specifics of any potential future collaborations until the very necessary discussions and negotiations are complete.

[1] Makris, N.C., P. Ratilal, D.T. Symonds, S. Jagannathan, S. Lee, and R. W. Nero. 2006. Fish population and behavior revealed by instantaneous continental shelf-scale imaging. Science 311: 660-663 (additional online supporting material at: www.sciencemag.org/cgi/content/full/311/5761/660/DC1)

SUMMARY OF WORKSHOP SESSIONS

PRELIMINARY SESSION
Monday January 29, 2007

Gary Melvin, DFO/SABS, opened the workshop on behalf of the Organizing Committee and introduced Michael Sinclair, (Maritimes) Regional Director, (DFO) Science Branch. Michael Sinclair extended an official welcome to all workshop participants on behalf of the sponsoring Department of Fisheries and Oceans.

Gary Melvin continued opening preliminaries, covering a range of housekeeping issues, and informed participants that both scheduled Introductory Speaker David Farmer and Session 1 speaker Orest Diachok could not attend due to unforeseen circumstances. In David Farmer's absence, Mark Trevorrow and Norman Cochrane had volunteered to cover conceptual and historical material appropriate to an introductory address (these alternatives presentations were developed at short notice independent of Dr. Farmer's materials or specific directions).

Norman Cochrane, DFO/BIO, of the Workshop Organizing Committee, was then introduced and proceeded to set forth the three-fold objectives of the workshop:

1) To explore the potential applications of long-range active sonar to fish stock assessment.

2) To assess the current "state-of-the-art" of long-range sonar for the above task.

3) To explore "next steps" (demonstration experiments, possible collaborations, availability of hardware and processing expertise).

Mark Trevorrow, Defence Research and Development Canada (DRDC) - Atlantic, initiated the topical introductory address "An introduction to long-range sonar, and its application in the detection of biological targets." Dr. Trevorrow's remarks are briefly summarized as follows: Fish are unevenly distributed in the ocean; acoustics has the unique distinction of being the only remote sensing tool that generally works well in the ocean. Most conventional fish sampling (assessment) techniques, including vertical echosounding, are constrained to sensing in the proximity of a surface vessel, precluding a true synoptic view of fish distributions. Long-range sonar can potentially answer the fundamental questions *where*, *when*, and *how many* in a synoptic manner, but it must deal with the complexity of sound propagation in the ocean. Low frequency towed array sonars are a mature technology applied to naval tasks with considerable potential for very wide area fishery surveying. Other acoustic fish assessment technologies include the traditional vertical beam echosounder which can be very accurately quantified but suffers from small sampling volumes and the possibility of target avoidance of the surveying platform. Medium frequency, side-looking, towed sonars ranging from simple mono-beam sidescans to complex multiple beamforming units, can significantly extend coverage laterally from the support vessel to perhaps as far as 10 km with potential for directing concurrent remote sampling. At longer ranges, these systems are subject to often unfavourable propagation effects which, like the case for lower frequency towed arrays, can sometimes be minimized by appropriate choice of tow depth. A variant of the towed array is the bottom-mounted side looking sonar. Such sonars are particularly suited for long term operation, supplying temporal information on fish migrations, especially if properly sited on rivers or other constriction sites where fish are forced to pass.

In quantifying sonar performance for a given target, a vital descriptive parameter is the signal excess above unwanted noise. This quantity is dependent on the source level of the sonar,

sound propagation losses to and from the target, the sound reverberation levels and ambient background noise levels characteristic of the environment, and the directivity index of the sonar which is a measure of how efficiently noise can be excluded by system directionality (sonar equation shown). The acoustic target strength (TS) of a fish at high frequencies is quite dependent on the direction of ensonification, the TS being greater broadside or at dorsal aspect than from fore or aft. Fish swimbladders resonate in the low frequency range (typically 200 – 1500 Hz for 30 – 50 cm length fish) producing a broad rise in TS near resonance with little directional dependence. Frequently, fish aggregate producing an unresolved school echo at range. In this case, one can define a school target strength (in decibels: $TS_{School} = TS_{Fish} + 10 \log N$ where N is the number of fish instantaneously ensonified).

Acoustic propagation characteristics are also important. These include propagation losses with range, spherical (20 log R) spreading for free propagation in deep water and cylindrical (10 log R) spreading when sound is constrained by top and bottom interfaces, scattering losses at both the sea surface and bottom, and acoustic absorption losses which decrease rapidly with frequency, becoming almost negligible below a few kilohertz – hence the use of low frequencies for very long-range sonars. Propagation conditions in the waters off eastern Canada vary seasonally (examples shown). During winter, sound speed often decreases near the surface enabling near-surface originating sound to be propagated to great ranges with reduced loss in a surface duct. In summer, the surface mixed layer produces generally downward refractive conditions for near-surface generated sound excluding it from the near-surface at range, while increasing sound interaction with the bottom and consequent propagation losses. Complex propagation and reverberation effects mitigate against good depth discrimination in side-looking sonar surveys.

Dr. Cochrane continued the introductory address with an historical perspective on long-range sonar fish detection as gathered from the available literature. One of the first serious studies of long-range sonar backscatter from fish was conducted by the (British) Admiralty Research Laboratory in the early 1960's. This originally classified work was conducted with a 1 kHz fixed bottom-mounted sonar off Perranporth on the north Cornwall coast. A linear receive array formed a single 4° receive beam directed north-northwest into the Bristol Channel. On transmit, a linear 100 Hz FM sweep was employed on a 4 s duration transmit pulse. Matched filtering on receive improved the time resolution to within a factor of 2 of the theoretical 10 ms - a remarkable signal processing achievement for the time. Echoes observed on signal delay versus observation time plots, some at target ranges of as much as 25 – 35 km, were eventually ascribed to fish (several plots from Weston and Revie (1971) were shown). The most prominent echoes appeared to arise from schools of *Sardina pilchardus* which, from several lines of evidence, were around 13 m in diameter. Strong semidiurnal tidal motions appeared superimposed on the echograms, which also displayed strongly contrasting backscattering characters between day and night. In 1966, the sonar frequency was increased to 1.85 kHz and the receive beamwidth narrowed to 2° resulting in fish aggregations being detected to 60 – 65 km ranges (Weston and Revie 1989).

The early British Admiralty bottom-fixed array studies constituted one impetus for the subsequent development of a portable long-range sonar with fisheries capabilities. By 1969 the Institute of Ocean Sciences, Wormley, had completed development of the Geological Long-Range Inclined Asdic (GLORIA) sidescan sonar, a sophisticated but massive - 7 metric tons - 10 m length – sidescan operating at 6.4 kHz. This system with a side-pointing 2° beam was mainly used for geological surveying, but early tests in the Sea of the Hebrides reported by Rusby et al. (1973) demonstrated the capability for systematic mapping of herring concentrations with detection ranges to 15 km.

Dr. Cochrane emphasized that the current American long-range fish sonar studies were not a outgrowth of the British work, but rather stemmed from an independent rediscovery of the phenomena. The early work of David Weston, Jack Revie, and co-workers still remains little known to many modern fisheries scientists.

Gary Melvin of the Population Ecology Section, St. Andrews Biological Station concluded the Introductory Session with an address titled "Issues in surveying pelagic fishes potentially amenable to long-range sonar: Atlantic herring as study case." Dr Melvin provided a general overview of the survey issues associated with pelagic fish species and used Atlantic herring as an example. In essence, there are two broad categories of commercial fish species, ground or demersal fish (e.g., cod and haddock) and pelagic fishes (e.g., herring and mackerel), which distinctly differ in their spatial and temporal distribution (behavioural/migration). Groundfish tend to be distributed dispersed horizontally near the bottom while pelagic fishes are distributed in aggregations in the water column that move up and down. Both groundfish and pelagic fish undertake annual migrations typically associated with spawning/feeding. Groundfish migrations are generally short in range, while pelagic fish migrations are longer and occur over several months. Herring and mackerel undergo extensive seasonal migrations.

Conventional groundfish surveys are conducted using a bottom trawl at random stations within a depth stratified design. Pelagic fishes are less amenable to bottom trawl surveys due to their vertical distribution, patchy occurrence, and diel migrations and are typically surveyed using acoustics. These factors also contribute to the difficulty in locating and documenting the distribution and abundance of pelagic fish species. The potential distribution of most pelagic fish species covers a very large area and there is limited vessel time for surveying. Long-range sonar could make a significant contribution to surveying pelagic fishes through the location of fish aggregations over a broad coverage area – search phase of a two phase design. Thereafter, traditional acoustic methods could be used to survey the fish. In addition, a broad scale synoptic survey could be used to monitor the movement of fish into and out of an area of interest. It is important to note that although herring is used as a study case, the approach and technology has broad pelagic ecosystem applications and is not restricted to a single species.

For Atlantic herring in the Scotia-Fundy region, there are three main stock components, Southwest Nova Scotia/Bay of Fundy (SWNS/BOF), Coastal Nova Scotia, and Offshore Scotian Shelf, all of which have different survey requirements. Currently SWNS component uses a series randomly selected transects within a defined survey box for each major spawning area to estimate spawning stock biomass (SSB). Multiple surveys are conducted at two week intervals, by fishing vessels equipped with calibrated acoustic logging systems, on each spawning ground. Biomass is determined by summing each survey estimate SSB. Recent studies indicate that fish may remain on the spawning grounds up to five weeks or more, thus double counting is a real issue. Herring are known to occur and spawn over a broad geographical area on the offshore Scotian Shelf. Unfortunately, the location, timing of spawning, and the distribution of fish is unknown.

Long-Range Sonar may provide a broad scale quantitative tool for locating herring and other pelagic fish species as part of a two phase survey design, provide information on the dynamic immigration/emigration of fish on to and off of the spawning grounds, and reduce the risk of double counting of fish in biomass estimates from multiple surveys.

SESSION 1. LONG-RANGE ACOUSTIC FISH DETECTION

Monday January 29, 2007 Chairman: Norman A. Cochrane, DFO/BIO

The Principal Scientific Address "Fish population and behaviour revealed by instantaneous Continental-Shelf scale imaging" by Nicholas C. Makris and co-workers was delivered by Prof. Makris of the Massachusetts Institute of Technology. Several previous reports of sonar detection of fish at relatively long ranges were noted. The earliest appears to be that of Isaacs and Swartzlose (1965) in which a U.S. navy sonar was used to image fish over a 360 degree sector to ranges of a couple of kilometers, where trawls later confirmed the presence of fish. The British sonar work of Weston and Revie (1971) using a fixed bottom sidescan and that of Rusby et al. (1973) with the towed GLORIA sidescan were also acknowledged and some relevant fish imagery shown. It was explained that a fundamental problem in conventional (vertical beam echosounder) and sidescan (synthetic aperture) acoustic fish stock assessment is the spatial/time aliasing on sampling large scale distributions of systematically moving targets. In contrast, the Ocean Acoustic Waveguide Remote Sensing (OAWRS) technique by use of a long-range beamforming sonar affords a true Eulerian reference frame for mapping fish distributions, thereby enabling an effectively instantaneous snapshot over fixed coordinates in space, as opposed to the Lagrangian nature of conventional surveys where spatial information must be gleaned over an extended time period from a moving observation point.

The OAWRS techniques evolved in the context of low frequency towed-array active sonar experiments designed to study clutter, and particularly geoclutter (discrete and prominent acoustic returns from geologic features of the seafloor or sub-seafloor) as a performance constraint on military-type sonars. Relevant studies were conducted in the 1990's in deep water at the mid-Atlantic Ridge and later in continental shelf waters of the STRATAFORM area off the New Jersey coast. The first detections of strong scattering areas at range in the STRATAFORM area were made in 2001. A fish aggregation origin for this backscattering was accepted only after: (1) direct experimental evidence from various supporting geologic surveys led to the failure of other plausible explanations, (2) theoretical calculations showed fish to be a more likely candidate, and (3) another experiment was conducted in 2003 to test the fish hypothesis with simultaneous measurements from a conventional fish finding sonar. During the 2003 experiment, a stationary vertical source array was employed in a bistatic geometry with a linear horizontal towed array receiver. The transmit waveform consisted of a wide-band frequency sweep. In addition to enabling pulse compression and signal-to-noise ration (SNR) enhancement, the wide band sweep and the inherent oceanographic fluctuations of the waveguide and distributed fish targets tended to smooth out the spatially variant nature of the source field characteristic of narrow band continous wave (CW) sources that arises from modal interference effects. For precise quantification of the sonar imagery, parabolic equation estimates of signal attenuation were computed over an x – y grid and these subsequently used to compute the true scattering strength of the extended fish assemblages. Fish aggregations were observed near the edge of the shelf generally between the 80 and 100 m contours, the larger scale aggregation features being of 5 – 20 km spatial extent but with considerable resolved detail at shorter spatial scales. Structures were shown to change with time, often with spatially narrow "bridging features" connecting larger areas of concentration. These observed spatial details and their time evolution constituted unique observations, possible only by the use of wide-area sonar. Two-dimensional spatial spectra of the inferred fish population densities for areas of both very high and somewhat lower density aggregation, demonstrated a fractal-like fall-off with increasing spatial frequency.

Inter-comparisons of OAWRS imagery and a conventional 38 kHz Naval Research Laboratory (NRL) echosounder transect across a large shoal were shown. Fish tended to be aggregated in the lower half of the water column with most of the biomass (some localized exceptions)

confined within a 10 m vertical interval. For precise quantification one could use a conventional vertical beam echosounder to establish an absolute local fish population density and then subsequently extrapolate the density over a much wider area using long-range sonar propagation-corrected measures.

When queried as to the fish species observed uncertainty was expressed; however, previous trawl surveys in the area would suggest scup, hake, or possibly herring.

Purnima Ratilal of Northeastern University proceeded to present the second talk titled "Spatial and temporal behaviour of Atlantic herring spawning on Georges Bank revealed by Ocean Acoustics Waveguide Remote Sensing." The presentation began with a discussion of the herring life cycle. Most adult Georges Bank herring tend to lie in the age 2 – 5 years range. Eggs hatch in 7 – 10 days, the subsequent larval and juvenile stages lasting about 6 months, and from 6 months to 2 years, respectively.

In the fall 2006, OAWRS bistatic sonar experiment on Georges Bank, a vertical array acoustic source was deployed by R/V *Endeavor* with the receiving beamforming array towed by the R/V *Oceanus*. Concurrent observations were made by Natural Marine Fisheries Service (NMFS) vessels equipped with Simrad EK60 echosounders and RESON 400 kHz multibeam sonars and with an additional trawl capability. The acoustic source was capable of wideband (50 Hz bandwidth) operation at center frequencies of 415, 735, 950, and 1125 Hz. The 950 Hz operational frequency appeared best for herring detection and a number of inter-comparison runs at 415 and 950 Hz were conducted.

The survey area consisted of the northwest side of Georges Bank. Approximate 100 km diameter sonar coverage was planned. An initial decision concerned optimum placement of the source. Since herring tend to spend the greater portion of time near-bottom, it was vital to obtain good ensonification to bottom in the deeper waters on the side of the Bank while maintaining some acoustic coverage of the upper water column. Propagation modelling showed this was best achieved by placing the source in deeper waters at about 60 m depth. Fish shoals were most visible in sonar imagery in the evening hours when fish tended to be near-bottom. An example of imagery containing a large 5 x 10 km shoal was shown. Conventional echosounding indicated dense fish concentrations ($\sim 1/m^3$) within the shoal. An extensive series of observations were conducted from Sept. 26th to Oct. 5th. Migrations of large fish shoals, generally from west to east on the Bank, could be systematically followed by the long-range sonar. In daylight hours, sonar backscatter was frequently diffuse becoming stronger and more distinct during the night, especially during the evening hours as noted above. Concurrent trawl samples consisted of over 99% herring. Sonar images of a large shoal ensonified at 415 and 950 Hz were compared. Differing portions of the shoal scattered more strongly at the two frequencies. This effect was not believed to arise from differing fish depths since at the time of observation the shoal would be expected to be near-bottom. One school followed over an extended time period moved systematically from about 200 m water depth to about 50 m water depth. This could reflect a spawning behaviour.

Tuesday January 30, 2007 Chairman: Gary D. Melvin, DFO/SABS

The third presentation "Examples from active sonar trials of direct-path and convergence-zone scattering off fish" was prepared by Roger Gauss of NRL and in his absence presented by Woody Nero, formerly of NRL, and now employed with National Oceanic & Atmospheric Administration (NOAA), Stennis Space Center. Below 10 kHz, the primary scattering mechanism of most fish is their air-filled swimbladder. The acoustic response of a fish depends on its swimbladder size, a function of the fish's size and depth. With regards to size, as the

swimbladder typically occupies just ~5% of a fish's volume, a fish generally can be treated as an isotropic scatterer, especially at low frequencies. As regards to depth, fish often have a diurnal depth dependence as illustrated by a depth x frequency plot of backscatter from Pacific hake off of Mendocino California, where the resonant peak varied from about 1500 Hz when fish were at 300 - 400 m depth (day) to about 900 Hz at 200 m (night). In short, fish scattering strength depends on fish size, depth, and (of course) density.

An example of how the acoustics couple with oceanography was shown for Pacific hake. In this case, the hake follow particular temperature contours, the spatial and temporal distributions of which depend on the climate. Given this knowledge and of fish-migration patterns, the spatial distribution of hake can be estimated as a function of time (e.g., by month) given the climatology. While the dynamism of fish makes it very difficult to make accurate predictions of scattering strength if high temporal and spatial resolutions are required, if the characteristics of the scatterers are well known then reliable seasonal predictions of mean scattering strengths can be made over relatively large areas using a combination of contemporary fishery data and a few validating measurements. Fluctuations in fish abundance (as well as migration patterns) imply that, in general, such predictions may only be expected to be valid for a few years. Furthermore, fishery data alone may be insufficient input to yield accurate predictions since fishery research typically only relates to species of (potential) commercial value. In short, both up-to-date fishery information and *in situ* sampling are required to make reasonable estimates of the local volume reverberation.

In direct-path geometries (ranges of ~0.1 - 3 km) recognizable broadband signatures identify fish presence and strength when they are well separated from the ocean surface or bottom, as was illustrated for Gulf of Alaska salmon (daytime) during the 1992 Critical Sea Test 7 (CST 7) experiment. This experiment displayed both a resonant peak in frequency at 500 Hz and a flattish grazing angle response at low scattering angles. The example also illustrated that due to their isotropic acoustic scattering, even small numbers of fish (in this case, ~200 per kilometer squared) can have a significant acoustic impact at low angles (and so at long-ranges where typically only lower-angle energy survives), in this case with levels up to 20 dB higher than backscattering from the air-water interface. However, when fish are in the vicinity of an ocean boundary, these characteristic fish signatures can undergo significant modification due to boundary-interference (Lloyd-mirror) effects. This response depends strongly on the incident and scattered grazing angles, the distance of the fish from the boundary, and the acoustic frequency. Examples were shown illustrating the complex acoustic response for salmon (night time; off Alaska) near the sea surface and for rockfish (off Oregon) near the seafloor. These examples showed that fish echoes can be confused with echoes arising from other scattering mechanisms (sea surface, seafloor), and that broadband measurements are needed to help sort out the mechanisms.

In long-range backscattering, low-angle energy predominates so that fish, being isotropic scatterers, can dominate the acoustic response, such as when they are in deep-water surface convergence zones. Some results from the 1988 CST 1 experiment in the Norwegian Sea were presented showing repetitive increases in backscatter of up to 20 dB, apparently arising from redfish and blue whiting, at the predicted times for echoes from successive surface convergence zones (ranges of ~40, 80, and 120 km). Long-range fish scattering can also be very important in shallow water where higher-angle propagating modes are quickly stripped off with increasing range due to frequent bottom and surface interactions. Therefore, in multipath environments most long-range reverberation will be due to shallow-angle acoustic interactions and so again favour isotropic scatterers like fish. It was also noted that fish in shallow water are more likely to aggregate into isolated schools than in deep water.

Narrowband fish echoes also display frequency shifts, either in the form of a frequency bias arising from systematic directional migration, or in the form of a broadening of the backscatter spectrum from more random motions, such as when fish are feeding. The acoustic impact is expected to be greatest at 500 - 5000 Hz, a trade-off between Doppler shifts being proportional to fish size (bigger fish swim faster), and inversely proportional to fish abundance (more small fish than big fish), coupled with fish frequency-resonance behaviour. Examination of Doppler broadening spectra from an ensemble of deep-water CST experiments revealed a close relationship between the observed Doppler spectra and theoretical model predictions assuming Gaussian fish motions predicted from mean fish length. Caution must be exercised when near-surface bubbles are present since they can produce similar Doppler broadening effects.

Presentations 4 and 5 concluding Session 1 treated experimental backscatter systems which, while not low frequency, still possessed multi-kilometer range fish detection capabilities, i.e., detection ranges lying between those of traditional ship-based high frequency fisheries multibeams and low frequency, towed array military-style active sonars, such as featured in Session 1, Presentations 1 and 2. Because of their inherently lower cost and size, these systems might be useful in specialized stock assessment applications.

Presentation 4 by Mark Trevorrow, now of DRDC - Atlantic, titled "Intermediate range fish detection with a 12 kHz sidescan sonar" concerned development and subsequent applications of a 12 kHz long-range fisheries sidescan at DFO's Institute of Ocean Sciences (IOS), Sidney, B.C. The instrument consisted of a 40 element 2.5 m aperture linear transducer array used in both transmit and receive resulting in a single broadside transmit/receive beam of 1.5° width. Transmit source level was 217 dB re 1μPa @ 1 m. Emitted pulses consisted of a 200 ms 1600 Hz bandwidth chirp. The entire system was mounted on in a rigid towed body with a variable depth capability. A block diagram of the electronic systems was shown, the sonar being constructed around an EDO Model 248 sonar receiver.

Results from 1997 and 1998 deployments in the Strait of Georgia were presented. In 1998, herring schools were detected at 3 – 4 km ranges near the mouth of the Fraser River verified by EK500 vertical beam transects from a second vessel. In 1997, a survey in the southern Strait of Georgia detected individual Sockeye Salmon (TS ~-32 dB) echoes out to lateral ranges of 7 km. Propagation analysis predicted strong sound channelling with up to a 24 dB enhancement of target echoes (narrow depth range) over two-way spherical spreading at the longest ranges. This level of echo enhancement was in good agreement with observations.

In 1997, the same array was also bottom-mounted in the Drodgen Channel, Denmark for profiling in either fixed or incrementally stepped rotational configurations. Detection and imaging of moving herring schools to 1200 m range was achieved in 10 – 14 m water depths.

The 12 kHz sidescan appeared to constitute a powerful tool for supplementing or even directing conventional sampling. Care is nevertheless required to properly calibrate the system and to properly understand propagation effects. Independent ground truthing should be undertaken.

Editors' note: It was learned shortly after the workshop that the IOS 12 kHz sidescan is still operational and is scheduled for use in the summer of 2007 by Svein Vagle (IOS) and other researchers to study migratory salmon in Johnstone Strait.

Presentation 5 was by John Horne, Chris Jones, and Mike Wolfson of the University of Washington titled "Development of mid-frequency multibeam sonar for fisheries applications." It was explained that a National Ocean Partnership Program (NOPP) funded effort is in progress to use mid-frequency acoustics to detect, enumerate, and identify pelagic fish populations. A

quantitative sonar mapping tool is needed for synoptic fish surveying from a moving or fixed platform that would furnish full and continuous spatial coverage about the platform while largely avoiding the quantification problems arising from variable angles of ensonification (as in traditional ship-based multibeams). A mid-frequency acoustic system offers the added advantage of considerable observation range. Efforts have been successfully undertaken to model sonar performance in terms of fish target responses, propagation path effects, and surface and bottom interface reverberation.

The current Pelagic Imaging Mid-frequency Multibeam Sonar (PIMMS) is a 10 kHz, 360° circular receive array (about 1.5 m diameter) in the horizontal consisting of 64 vertically-oriented 2-element transducer dipoles beamformed to yield a horizontal circular fan of 4° beams. A separate vertical linear array in close proximity to the circular array furnishes an omni-directional horizontal transmit pattern of 8° vertical beamwidth. The vertical transmit array is deployed in Mills Cross arrangement with the horizontal receive array. Commonly, 10 ms transmit pulses are employed at a source level of about 192 dB re 1 μPa @ 1m. The whole sonar assembly can be lowered vertically from a vessel resulting in a series of circular horizontal slices of the water column at predetermined depths. Results from a preliminary Gulf of Alaska deployment revealed echoes from walleye pollock and other species. The compact and symmetrical nature of the unit should make it especially suitable for mounting on an Ocean Observatory.

SESSION 2. LONG-RANGE ACTIVE SONAR DETECTION AND QUANTIFICATION OF FISH

Tuesday January 30, 2007 Chairman: Dale D. Ellis, DND/DRDC - Atlantic

Session 2 explored miscellaneous technical and operational issues relevant to the use and performance of active sonar in fisheries applications. Peter Smith, Ocean Sciences Division, initiated the session with a general presentation "An overview of oceanographic conditions in the Gulf of Maine/Bay of Fundy." The identified regions are relevant to the fall 2006 Georges Bank active sonar experiment and border on or contain the herring spawning areas of high priority for future sonar survey off southwestern Nova Scotia and in the Bay of Fundy. Waters in the Gulf of Maine (GOM) arrive from the adjacent Scotian Shelf and offshore regions to the northeast and exit to the New England Shelf to the south. While the central GOM gyre is subject to strong summer density stratification from solar insolation, intense semidiurnal tides work to homogenize the water column over the shallower portions of Georges Bank, the Nantucket Shoals, the upper reaches of the Bay of Fundy, and around the southwestern portions of Nova Scotia. Marked frontal zones separate mixed and stratified areas. A generally cyclonic flow is maintained around the periphery of the GOM with anti-cyclonic flow around Georges Bank driven by both upstream forcing and tidal rectification. At longer time scales, the GOM is influenced by the annual spring freshwater discharge pulse from the Gulf of St. Lawrence which typically arrives at the eastern entrance of the GOM in the late fall, thereafter taking a further 6 – 8 months to circulate the GOM periphery. Still longer term influences arise from the North Atlantic Oscillation (NAO). Low NAO index conditions tend to allow large volumes of Labrador Slope water to pass westward along the continental slope of Atlantic Canada at depths of several hundred meters. A portion of this flow typically floods the deep portions of the Scotian Shelf basins connected to the continental margin by deep silled channels and, as well, floods the deep GOM basins. A time lag of 2 – 3 years may occur between low NAO indices and resultant changes in the GOM. This effect was illustrated by reference to a low NAO event in 1996, which was linked to changes in the Scotian Shelf fishery and a cold water intrusion in the deeper portions of the GOM in late 1997, with recovery in 1999. "Sustained anomalies" in which the same (especially winter) NAO anomaly sign persists for at least 2 years are likely to have greater ecosystem impacts than shorter term index excursions.

Editors' note: While it was not the intention of this presentation to treat the influence of oceanographic conditions on acoustic propagation, it was apparent that acoustic propagation conditions in the region would be highly variable. For instance, modelling acoustic propagation from the Gulf of Maine toward the shallow herring spawning areas of Georges Bank or German Bank would require the careful quantification of sound speeds in the transition from a modestly to strongly stratified regime offshore to a well-mixed region on the actual spawning grounds. The actual sound speed structures might be expected to show considerable variability month-to-month and from year-to-year requiring survey-particular TS controls rather than a reliance on long term statistical norms.

The performance of active sonar for a given task, such as fish school detection, can be closely approximated by the active sonar equation, given the quantitative characteristics of the sonar system, the propagation environment, and the assumed characteristics of the acoustic target (fish) aggregations. In Presentation 2 titled "Long range sonar performance (sonar equation, propagation and reverberation considerations)," Sean Pecknold, John Osler, and Dale Ellis of DRDC - Atlantic presented a detailed study of acoustic propagation and the attendant projected fish detection capabilities of a given sonar system. Two relevant study areas were chosen, the first on northern Georges Bank and the second at the mouth of the Bay of Fundy south of Grand Manan Island. Transmission losses were calculated along 18 directional radials centered on each site for several fish school depths, ranging from the near-surface to 80 m on Georges Bank and to 150 m in the Bay of Fundy. The Bellhop acoustic propagation model, modified to incorporate both surface and bottom scattering losses and also incorporating realistic sub-bottoms, was used for transmission loss calculations. Computed transmission losses at 1 kHz for a source at mid-water column depth were computed using seasonal ocean climate data. Losses were generally both higher and more directionally variable in the Bay of Fundy than on Georges Bank. Assuming a sonar approximating the DRDC TIAPS system operating with a 1.8° receive beamwidth and with a VP2 omni-directional source emitting a 100 ms pulse, detection ranges for a mid-water unresolved herring fish school of 20 dB target strength on using a 10 dB signal above noise criteria would be about 15 - 20 km for the Bay of Fundy and about twice that range for Georges Bank. The sonar noise background should be reverberation limited in fair weather for source levels down to about 190 dB in both areas at these ranges.

Presentation 3 titled "Ambient noise background in coastal waters of Eastern Canada," was delivered by Francine Desharnais, DRDC - Atlantic. Two historical open-literature references were identified as being of particular value:

- Piggott (1964) – *Perhaps the most useful reference for the Scotian Shelf (8.4 to 3100 Hz) as ship noise has been removed. The measurement area, which could not be stated at the time, was near Halifax.*
- Wenz (1962) – *Levels tend to be about 2 - 7 dB lower than those reported by Piggott.*

More recent work includes the collected historical measurements of Zakarauskas et al. (1990) which, in addition to the Scotian Shelf, cover the Laurentian Channel, Grand Banks, and Flemish Cap; and the 1995-1996 Eastern Canada Shallow-Water Ambient-Noise (EC-SWAN) measurements in which monthly noise levels and their spatial variability were explored using sonobuoy techniques at 4 sites on the eastern Canadian Shelf (Hazen and Desharnais 1997). Measurements covered the 10 – 2500 Hz frequency range with some data up to 32 kHz.

Unpublished measurements in the Bay of Fundy (July 1999) from 10 – 200 Hz generally follow the Wenz curves for high shipping areas. From 200 - 800 Hz, Bay of Fundy levels are 2 – 5 dB above the shallow water Wenz curves.

In summary, some "rules of thumb" were advanced for Scotian Shelf noise levels:

- Finback whales produce strong spectral peaks around 20 Hz from October to January and can elevate background noise levels by 20+ dB.
- For the shipping band 10 – 200 Hz, noise levels follow moderate to high shipping level Wenz curves for shallow water.
- Above 200 Hz Piggott is best; Wenz and Knudson et al. (1948) tend to be too low. Few measurements exist above 3 kHz.

Attention was then turned to the issue of fish target strengths and its variation with acoustic frequency, ambient pressure, and frequency. In Presentation 4, "Target strength issues in conventional high frequency assessment of herring," Michael Jech, NOAA/NMFS/Woods Hole, outlined what is known about the target strength of herring in the high frequency range employed by conventional vertical beam fish assessment echosounders. It was explained that NOAA - Fisheries herring surveys in the Gulf of Maine are conducted at 12 or 18, 38, and 120 kHz using Simrad EK500 sounders and hull-mounted transducers - a 38 kHz transducer can also be lowered to the fish concentrations - with ground truthing from pelagic trawls. Acoustic survey data are processed and archived in real-time, including target strength data. Examples of acoustic and trawl survey data collected on Georges Bank were presented showing variations in echogram character with frequency, temporal variations within yearly surveys, and between surveys. It was pointed out that acoustic measures can be useful indices of abundance and with careful target strength studies, good absolute abundance and biomass estimates can be produced. Target strength has been investigated using in-situ echosounder measurements, ex-situ laboratory TS measurements of live fish, and theoretical studies using the Kirchhoff-ray mode model applied to measured fish and fish swimbladder morphologies. A number of examples were shown with emphasis on herring. Theoretical models show good agreement with both lab and field TS measurements. U.S. measurements of herring target strengths (typically -35 to -36 dB) appear reasonably self consistent but are significantly higher (about 5 – 6 dB) than those reported by Norwegian researchers, a result that is yet to be fully explained.

In Presentation 5 "Low frequency acoustic backscatter characteristics of targeted fish and fish assemblages," Woody Nero, former NRL now NOAA/NMFS/Stennis, addressed the low frequency scattering properties of swimbladdered fish. This topic was studied by NRL particularly between 1988 and 2001 in regard to the performance of low and medium frequency naval sonars. Swimbladders of most fish resonate in a depth-dependent fashion in the frequency range of 500 Hz to several kilohertz. Early NRL experimental measurements of volume backscatter, a phenomena often dominated by fish backscattering, used small explosive sources (1/2 lb of TNT) detonated close to and vented to the surface with broadband recording of volume reverberation. More recently, electrical acoustic sources have been employed. An adaptation of the Love (1978) swimbladder resonance model has proven quite successful in predicting low frequency fish-dominated volume reverberations levels and their frequency spectra. These predictions can be extended to tightly packed ensembles where the scatterers interact. A sample computation of the average fish target strength of several ensembles of Atlantic Canada herring of published length distributions at both shallow and deep water depths was presented. The dominant swimbladder resonance frequency and its depth dependence may afford a degree of species identification. This concept was illustrated by selected examples from past NRL studies. A particularly relevant study of the theoretical and observed broadband scattering characteristics of Gulf of Maine herring was undertaken between NRL and NMFS in 2001, with reasonable agreement between theory and observation. Herring at depth would appear to have larger than anticipated swimbladder gas volumes, the origin of this excess has not yet been satisfactorily explained.

The final two presentations of Session 2 described the hardware necessary to conduct low frequency active sonar experiments. The rationale for soliciting these presentations was to better define the magnitude of effort and necessary resources to achieve such objectives, as well as to inform the audience about specific hardware systems that might potentially be available for future experiments by way of lease or cooperative venture. Two systems were considered: the ONR Five Octave Research Array (FORA) and the DRDC - Atlantic TIAPS array.

In Presentation 6, "The ONR Five Octave Research Array (FORA) at Penn State," John Preston of the Applied Physics Laboratory, Penn State University, described the FORA. This reception array was designed and built by Chesapeake Sciences Corp. under the oversight of Penn State University and with the assistance of Teledyne Instruments. It was used during the 2003 Geoclutter experiment on the New Jersey Shelf, as well as in the 2006 Georges Bank LF acoustic experiment. The FORA consists of 4 nested linear apertures with cut-off frequencies of 250, 500, 1000, and 2000 Hz plus a separate high frequency array of triplet hydrophones capable of generating a cardioid reception response pattern (removing the left-right directional arrival ambiguity associated with simple linear arrays of non-directional elements). The acoustic sections occupy about 220 m of the 277 m array, not including a trailing passive drogue. Three non-acoustic sensor (NAS) sections provide attitude, depth, and temperature data.

FORA is typically towed at 4 - 5 knots, flow noise setting an upper speed limit of about 6 knots. Maximum tow depth is 350 m. Total weight of array and winch is about 19,000 lbs. No specialized vessel is required to physically handle the array but a low tow vessel noise signature is advantageous. Array hydrophones are digitized at up to 25 kHz at 24 bits, of which 19 bits carry information. Acquisition is LINUX-based with maximum telemetry rates of 155 Mbits/sec.

During the Geoclutter experiment, the acoustic source consisted of a vertical array of XF4 sources. Interleaved XF4 and MOD 30 flextensional acoustic sources were suspended below the shooting vessel in a rigid frame. A 400 Hz on-axis source level of about 216 dB re 1 μPa @ 1 m was used from the XF4 elements. Use of the higher frequency MOD 30 gave similar levels.

In discussion following the Preston delivery, the questions of array capital and maintenance costs were raised. These questions were admittedly difficult to answer since FORA is not a mass produced item. Replacement costs of the wet end might be in the neighbourhood of $1.3M, and the dry end about $200K. The cardioid triplet section would account for about half the replacement cost. Refurbishment costs after a sea mission would be in the range of $50 - 60K. Lifetimes again are hard to estimate, but 10 – 15 years might not be unreasonable.

In the session concluding Presentation 7 "Overview of the DRDC towed array and source," Dale Ellis, DRDC - Atlantic, made a short presentation on the Canadian Towed Integrated Active Passive Sonar (TIAPS); Sean Pecknold, the primary author, being unable to be present. TIAPS operates in conjunction with either a vertical or horizontal array towed source. The VP2 vertical source is a dual ring projector radiator producing an omni-directional radiation pattern in the horizontal plane. Maximum levels are >220 dB re 1 μPa @ 1 m from 1 - 2 kHz. The VP2 source is towed by the same vessel as, but physically separate from, the receive array. The HPA horizontal projector is a 32 element barrel-stave radiator array towed in-line as an integral part of the TIAPS array, and has a beam-steering capability in the frequency range 1 - 1.3 kHz. Receive array components include the Digital Directional Acoustic Sensor Module (DASM), and Multi-Aperture Networked Towed Array (MANTArray). The DASM consists of 96 Combined Omni-Directional Resolved Sensor (CORDS) units (192 channels total) allowing resolution of

left-right ambiguity. The MANTArray consists of 256 channels comprising sub-arrays or modules of more conventional acoustic sensors. These include 2 modules of 1500 Hz cut-off frequency, 6 modules of 750 Hz cut-off, plus several lower frequency modules - the latter synthesized by sub-sampling elements of the higher frequency modules. All channels of both the DASM and MANTArray are sampled to 24 bits at a rate of 4096 Hz. Broadside receive beams as narrow as 1° can be formed. Total array length is 1.7 km including the forward end 600 m neutrally buoyant tow cable.

Discussion raised the issue of supporting processing and display software. Software was described as well "worked-up". However, current user interfaces are oriented toward military targets and associated operational objectives. Data formats are fairly similar to American systems (such as the FORA array); some effort has been expended toward standardization.

In the following general discussion, the possibility of collaborative low frequency sonar experiments with DFO was raised. Initial responses seemed positive but specifics were not discussed. The need for an acoustically quiet fisheries vessel (for instance meeting the International Council for the Exploration of the Sea (ICES) noise specification) to do verification sampling during a large area LF survey was emphasized. Vessel noise can degrade LF sonar displays as well as bias verification sampling due to vessel avoidance. Working near the swimbladder resonance frequency would have advantages in terms of a more omni-directional target response, as well as some possibility for species discrimination especially if very broadband or multiple frequencies can be transmitted.

SESSION 3. ENVIRONMENTAL CONSIDERATIONS

Wednesday January 31, 2007 Chairman: Gary Melvin, DFO/SABS

Low frequency, long-range sonar systems have the potential to interact with a number of marine organisms, especially marine mammals and fish. If a project utilizing low frequency sonar technology was to be undertaken in Canadian waters, then consideration must be given to the organisms contained in the prospective large zone of influence. The purpose of this session of the workshop was to provide an overview of the available information on the distribution of species likely to occur in the Bay of Fundy, off southwest Nova Scotia and on the Scotian Shelf, as well as their sound detection levels. Particular attention was paid to identifying the temporal and spatial distribution of marine mammals in the region.

The first paper in this session titled "Spatial and temporal distribution of marine mammals in Southwest Nova Scotia/Bay of Fundy region" by Kent Smedbol provided a general overview of the broad scale distribution of marine mammals. Smedbol categorized marine mammals into four groups; seals, dolphinds, toothed/beaked whales, and baleen whales and provided generalized distribution maps for each group. Three species of seals were identified in the region; grey and harbour seals which live year round in the region. Both species breed on Sable Island, but the harbour seals also breed elsewhere. Harp seals are summer and fall visitors to the region.

Several species of dolphinds occur in the region including: harbour porpoise, white-sided dolphin, common dolphin, white-beaked dolphin, and long-finned pilot whale. Most species can found in the Bay of Fundy, and along the edges of offshore banks and the shelf in late summer. However, harbour porpoise tend to be more coastal in their distribution. Whales in this region were grouped into toothed/beaked whales (sperm whale, northern bottlenose whale, and orca), which are deep divers that generally occur offshore, and baleen whales (blue, north Atlantic right, finback, minke, humpback, and sei whale) of which the blue and northern Atlantic right

whales are listed as endangered. Most whale species are found throughout region, but sightings are concentrated in Bay of Fundy, around offshore banks, and along shelf edge. The latter species undergo a seasonal north/south migration and are primarily observed in the summer/fall. There are also three important areas in the region; the Bay of Fundy and Roseway Basin Conservation Area for right whales and the Gully Marine Protected Area east of Sable Island.

In summary, marine mammals occur throughout the area of interest for a low frequency sonar study and must be considered in a project proposal.

The second talk titled "Effects of low frequency anthropogenic sounds on marine mammals" by Jack Lawson from the DFO Northwest Atlantic Fisheries Centre, St. John's, Newfoundland and Labrador, provided an overview on detection levels and the potential impact of sound on marine mammals. The presentation identified the characteristic hearing ranges of several groups of marine mammals. Potential effects of LF sonar on marine mammals will be a function of several factors including output power, beam width and duty cycle, frequency, and transmission characteristics. Medium (1000 to 10000 Hz) to low (10 to 1000 Hz) frequency transmissions overlap with the call frequencies of most marine mammals and are likely to have some level of impact. The long-range detection of fish will require a high source level and for frequencies of <1 kHz signal attenuation is negligible. By comparison, the maximum sound output for low frequency baleen whale calls range from 165 to 210 dB re 1 μPa.

Data on cetacean hearing sensitivity and hearing dynamic range are limited and differ among species. However, Lawson described the measured or predicted hearing characteristics for a number of mammals. Given these data, sound emitted during a LF sonar study would be detectable by many species of marine mammals, but not always in their best hearing sensitivity range.

Potential impacts were scaled into mild to serious injury levels. At the lower end of the scale was masking of acoustic activities, which could interfere with social communication and foraging, followed by behavioural disruption that might displace the mammals from important feeding or breeding habitat. The next level of impact involved the temporary or permanent threshold shift in hearing sensitivity resulting from exposure to high source levels. It was postulated that while a temporary shift may occur, it is unlikely a marine mammal would remain in an area long enough for permanent damage to occur. The most serious category would be direct and indirect injury (which could lead to death in certain circumstances), but this would likely only occur in unusual situations. For the SURTASS low frequency sonar programme the U.S. Navy established the following exposure criteria for marine mammals:

- Awareness = 120 dB.
- Behaviour modification =140 dB.
- Potential impact = 160 dB.
- Received SPL should not exceed 160 dB for a species.
- Source ramp-up required when received level ≥180 dB.

In summary, there is a high degree of uncertainty in quantifying or identifying the effects of LF sonar on marine mammals. Mitigative measures include identification of species that might be present in the study area, estimation of "safety zone(s)" around the sound source, visual and acoustic monitoring for mammals, ramping up for high source levels, as well as shutting down or decreasing source level when mammals are present within the safety zone(s). Propagation models and field sound level measurements should also be undertaken to determine the potential zones of influence. Given emerging information on stranding deaths for some species

exposed to mid-frequency military sonars, such as beaked whales, efforts should be made to avoid exposing them to these types of sounds.

Presentation 3 titled "Effects of low frequency sound on fish" was given by Svein Løkkeborg from the Institute of Marine Research, Bergen, Norway. The talk began with an overview of how fish in general use sound, their ability to hear, and how they respond to anthropogenic sound. This was followed by a review of behaviour studies, fishing experiments and studies specific to herring. In essence, fish use sound for locating prey, avoiding predators, and for social interaction. The ability of fish to hear varies from species to species but, can be grouped into two broad categories: generalists and specialists. Like marine mammals, there are several similar levels (minor to severe) of potential impacts from anthropogenic sound. Løkkeborg identified the following:

- Masking of communication that may affect growth, survival, reproduction.
- Temporal threshold shift.
- Cessation of feeding.
- Disturbance/disruption of spawning.
- Change migration routes.
- Damage.
- Death.

He then went on to provide specific examples of how fish react to different sound levels and frequencies. Most of the studies he presented examined frequencies between 10 Hz and 1 kHz with a range of source levels. In one example, the response of rockfish to an air gun were: undirected movement at 154 dB, changes in depth distribution and milling at 162 - 168dB, alarm response around 180 dB, and a startled response at 205 dB. The impact on fish catch rates due to seismic surveys were found to decrease between 20 and 85% depending upon the study. Several studies on herring indicate they are far more sensitive to sound than many other species and that they have a wide frequency response range. Herring may respond even when other species do not. A startle response follow by abnormal swimming was observed in one study at 180 - 189 dB.

In summary, fish are affected by low frequency sound, but little is actually known about the effects on migration, spawning, feeding, masking, and temporal threshold shift. Avoidance of low frequency high source levels is the most likely response and could affect commercial catch rates, migration routes, and/or cause fish to move away from feeding and spawning grounds. However, fish associated with an underwater feature are unlikely to move away from the feature.

The final presentation titled "Sonar R&D risk management: potential impact on marine mammals" was given by Francine Desharnais for Jim Theriault of Defence Research and Development Canada (DRDC) in Dartmouth, Nova Scotia. DRDC has undertaken a number of low frequency experiments over the years. Their approach since adopted into Canadian law (e.g., Oceans Act 1996) has been to follow the principles of the precautionary approach resulting from the 1992 United Nations Rio Declaration. Principles under the precautionary approach include:

1. Legitimacy of Approach.
2. Chosen Level of Protection.
3. Sound Scientific Information.
4. Burden of Proof.
5. Re-evaluation and Further Consultation.

6. Transparency, Accountability, and Public Involvement.
7. Provisionality.
8. Proportionality.
9. Non-discrimination and Consistency.
10. Cost Effectiveness.
11. Least Trade-restrictive.

Two applications were presented as examples of how these principles were applied: TIAPS R&D Sea Trial where the requirements included calm seas, deep water (>1000 m) and low ambient shipping, wind and biological noise; and the Exuma Sound in Bahamas (2001), where there were concerns expressed about the impact on marine mammals and a heightened public concern due to seismic activity and U.S. low and medium frequency active sonar trials. Prior to the sea trials a completed environmental assessment matrix was developed for the project that involved all the stakeholders. A number of criteria were established to manage the risk of impact on marine mammals during the trials and there were post-trial contingencies plans, monitoring, and a review of the lessons learned. A suite of new technologies and predictive tools to mitigate impacts were also reviewed.

In summary, through mitigation measures based on environmental risk within a public context and risk management before, during, and after the activity, DRDC was able to meet the experimental requirements without measurable environmental impact.

Editors' note: Orest Diachok, Poseidon Sound, Oakton, VA, was originally scheduled to deliver a presentation in Session 1 of this workshop titled "Bioacoustic Absorption Spectroscopy." Unfortunately Dr. Diachok had to cancel at short notice. Since his talk was closely related to the theme of this workshop and relevant to the wider objectives being pursued by DFO, of which the workshop is a component, Dr. Diachok was invited to present his material at a seminar at BIO on Feb. 23rd, 2007. A running summary of his BIO presentation is included as Appendix 4 to the proceedings.

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SUBMITTED ABSTRACTS / REFERENCES

A number of workshop authors have furnished abstracts of their presentations and/or listed additional reference materials. These are reproduced below:

SESSION 1. PRINCIPAL SCIENTIFIC ADDRESS

Fish Population and Behavior Revealed by Instantaneous Continental Shelf-Scale Imaging

Nicholas C. Makris,[1] Purnima Ratilal,[2] Deanelle T. Symonds,[1] Srinivasan Jagannathan,[1] Sunwoong Lee,[1] Redwood W. Nero[3]

Continental shelf environments are traditionally monitored with highly localized line-transect methods from slow-moving research vessels. These methods significantly undersample fish populations in time and space, leaving an incomplete and ambiguous record of abundance and behavior. We show that fish populations in continental shelf environments can be instantaneously imaged over thousands of square kilometers and continuously monitored by a remote sensing technique in which the ocean acts as an acoustic waveguide. The technique has revealed the instantaneous horizontal structural characteristics and volatile short-term behavior of very large fish shoals, containing tens of millions of fish and stretching for many kilometers.

There is substantial evidence that fish populations are rapidly declining worldwide, yet with conventional sea-going survey methods it is difficult to accurately enumerate fish populations and nearly impossible to study the behavioral dynamics of very large social groups or shoals of fish, including the impacts of population decline. This is because conventional methods rely on highly localized measurements made from slow-moving research vessels, which typically survey along widely spaced line transects to cover the vast areas that fish inhabit, and so greatly undersample the environment in time and space, leaving highly ambiguous records. We assessed fish populations with a remote sensing technology involving ocean acoustic waveguide propagation that surveys at an areal rate many orders of magnitude greater than that of conventional fish-finding methods. The waveguide technology makes it possible to continuously monitor fish population dynamics, behavior, and abundance, with minute-to-minute updates over thousands of square kilometers, producing records without aliasing in time and space.

[1] Center for Ocean Science and Engineering, Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.

[2] Department of Electrical and Computer Engineering, Northeastern University, 409 Dana Research Center, Boston, MA 02115, USA.

[3] Naval Research Laboratory, Stennis
Space Center, MS 39529\uffff\u20135004, USA.

SESSION 1 PRESENTATION 2

Spatial and Temporal Behaviour of Atlantic Herring Spawning on Georges Bank Revealed by Ocean Acoustics Waveguide Remote Sensing

Purnima Ratilal
Northeastern University

An ocean acoustics waveguide remote sensing (OAWRS) system was deployed on the Northern flank of Georges Bank, in the Gulf of Maine, in Sep-Oct 2006 to instantaneously image marine life over a 100 km diameter area. OAWRS utilizes the property of the ocean as a waveguide to channel audible sound waves over long ranges to image objects at great distances from the sonar system. Massive migration and spawning behavior of Atlantic herring was observed over several diurnal periods, including movements on and off the bank to spawn.

Measurements made concurrently with a 38 kHz conventional fish-finding echosounder provided information on the depth distribution of herring in the water column. Data were also collected using a 400kHz multibeam sonar providing the local 3D morphology of small fish schools.

Concurrent trawls surveys provided identification of the fish species.

Resonance scattering from fish was observed in OAWRS imagery over multiple frequencies. Findings from this experiment will be presented and discussed.

SESSION 1. PRESENTATION 3

Examples from Active Sonar Trials of Direct-path and Convergence-zone Scattering Off Fish

Roger Gauss
Naval Research Laboratory, Washington, DC

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SESSION 1. PRESENTATION 4

Intermediate Range Fish Detection with a 12kHz Sidescan Sonar

Mark V. Trevorrow
DRDC Atlantic, Dartmouth, Nova Scotia

Traditional net-trawl and echo-sounder surveys suffer from limited sampling volumes and areal coverage, and vessel-avoidance behaviour by the fish. The effects can be profound in coastal areas where fish aggregations can be highly localized. High-frequency (HF, >10 kHz) sidescan and multi-beam sonar technologies offer a variety of potential solutions, enabling detection and quantification of fish over much larger distances and water volumes, and operating at ranges where the fish are un-affected by the vessel presence. Bottom-mounted HF sonars can also provide monitoring of strategic migration routes, providing indices of migration rates and timing. Against these advantages, fish detection in a side-looking geometry is complicated by back-scattering from boundaries (surface and seabed), boundary reflections, and acoustic refraction. A further complication at high frequencies is the angular dependence (i.e. side, head, or tail-incidence) of fish target strength, making fish quantification difficult. Thus, in a fishery survey it now becomes necessary to understand fully the acoustic propagation environment in the survey region. A cooperative survey approach is advocated, combining the wide areal coverage of a

long-range sonar with the localized ground-truthing provided by traditional echo-sounder and net-sampling surveys.

The capabilities of both fixed-installation and towed sidescan sonars for fish detection in a variety of coastal and riverine environments have been experimentally demonstrated by the author and others. In particular, work in the 1997-99 period at IOS with a 12 kHz sonar is reviewed for the case of salmon in the Strait of Georgia, and migratory herring schools in Denmark. Examples of individual fish and fish school detection at ranges of order 100 to 7000 m are shown, illustrating a variety of acoustic propagation features. In vessel-mounted or towed applications, the spatial distribution of individual fish, or fish school size and morphology, can be directly measured.

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SESSION 1. PRESENTATION 5

Development of Mid-frequency Multibeam Sonar for Fisheries Applications

John K. Horne, Christopher D. Jones, Michael A. Wolfson
University of Washington

Acoustic data from echosounders and vessel-based surveys lack temporal synopticity, spatially interpolate densities from parallel transects, and may bias target intensities through angle-dependent (i.e. directivity) backscatter. A quantitative mapping tool that increases horizontal range could be used in isolation or in conjunction with traditional techniques to improve accuracy and precision of acoustic-based mapping and abundance estimates of pelagic organisms such as fish and zooplankton. Characteristics of a new acoustic tool would a lower (<38 kHz) frequency to increase operational range, omni-directional horizontal transmission and reception, and a configuration that was easily and quickly deployable in stationary (e.g. mooring) or mobile (e.g. vessel-based surveys) applications.

This National Ocean Partnership Program (NOPP) supported project is investigating the utility of mid-frequency (1-10 kHz) acoustics to detect, enumerate and identify pelagic fish distributions. Ongoing research tasks will integrate: 1) comparisons of fish backscatter, 2) mid frequency sound propagation, 3) development and measurements from a mid-frequency multibeam sonar, and 4) backscatter measurements using splitbeam echosounders and the multibeam sonar.

Backscatter modeling is used to examine pelagic fish species as acoustic targets and sound propagation in the waveguide. At 10 kHz, directivity of gas-filled, swimbladdered pelagic fish species is limited. Larger gadoid species such as walleye pollock (*Theragra chalcogramma*) and Pacific hake (*Merlucius productus*) are more directive than forage fish species such as capelin (*Mallotus villosus*) or Pacific herring (*Clupea harengus pallasi*). Sound propagation modeling is examining multipath backscatter and reverberation effects from rough surface and bottom. A full wave computational model based on the Para-axial approximation to the Helmholtz wave equation is used to estimate the interference bias effect from multi-pathing and bottom types. Rough surface and bottom conditions have not yet been explored. Propagation and target backscatter modeling will be combined to compare direct and multipath backscatter to sonar measurements.

The **P**elagic **I**maging **M**id-frequency **M**ultibeam **S**onar (PIMMS) is a 10 kHz (4 kHz bandwidth) omnidirectional sonar consisting of a 128 element circular array with vertical (transmit) and horizontal (receive) beam steering. The Mill's cross geometry results in an 8° transmit by 4° receive beams. The instrument is cabled to provide power and an Ethernet interface.

Field measurements will be conducted during two separate NOAA/NMFS acoustic-based biomass surveys of walleye pollock and Pacific hake in the northeast Pacific. Walleye pollock are found in a boreal ecosystem with low species diversity. Pacific hake are found offshore of the west coast of North America in a temperate, high diversity ecosystem. Preliminary analysis of data collected in the Gulf of Alaska show that daytime aggregations of walleye pollock and forage fish species were detected by the PIMMS sonar and by 18 and 38 kHz echosounders.

SESSION 2. PRESENTATION 1

An Overview of Oceanographic Conditions in the Gulf of Maine/Bay of Fundy

Peter C. Smith
Ocean Sciences Division, DFO, Bedford Institute of Oceanography

The dominant features of the Gulf of Maine/Bay of Fundy circulation are related to the semidiurnal tides, which are nearly resonant in the system. Strong semidiurnal tidal currents are primarily rotary in offshore areas, somewhat larger on the shallow banks than in the deep interior basins. However, the largest currents (~2-4 ms^{-1}) are rectilinear and found in the upper Bay of Fundy, where the tidal range is of order 16m. Intense tidal mixing causes certain shallow areas of the Gulf (Georges Bank, Southwest Nova Scotia, Nantucket Shoals) and in the Bay of Fundy to remain well-mixed throughout the year, in spite of the stratifying influence of solar insolation. Strong and persistent fronts between well-mixed and stratified regions have been shown to correspond to areas where a fixed fraction of tidal dissipation is able to work against gravity to eliminate stratification (Garrett, *et al.*, 1978). However, further wind mixing must be invoked to explain the presence of similar features in coastal areas of Maine (Loder and Greenberg, 1986).

Beyond the tidal effects, the circulation of the Gulf of Maine/Bay of Fundy exhibits a rich spectrum of variability, ranging from the "weather band" (periods of 2-10 d) to strong annual and interannual signals. The mass and freshwater transports through the Gulf exhibit a strong annual cycle, to some extent related to the annual freshwater pulse from the Gulf of St. Lawrence, which is generated in the April-May period and arrives at the eastern entrance to the Gulf of Maine (off Cape Sable, NS) in Nov-Dec (Smith, 1983), then makes a 6-8 month circuit around the Gulf, and exits southwestward to the New England shelf.

While the surface waters enter the Gulf from the Scotian Shelf via two pathways (inshore: Cape Sable, offshore: Browns Bank), the deep water properties are controlled primarily by communication with the slope waters through Northeast Channel. Two distinctly different "brands" of slope water (Warm Slope Water and Labrador Slope Water; Gatien, 1976) are available with characteristic temperatures and salinities differing by as much as 4°C and 1, respectively. This interplay can lead to drastic changes in the ambient conditions of the deep basins of the Gulf.

Changes in the slope water regime appear to be related to climate variability over the North Atlantic, as measured by the North Atlantic Oscillation (NAO) index, which measures the difference between the two major atmospheric centres of action over the North Atlantic, the Icelandic Low and the Azores High. Correlations between the NAO and the northward excursions of the Gulf Stream north wall and the shelf slope front off the Scotian Shelf are strongly positive with the frontal movements lagging the NAO by 1-2 years. During low NAO, the southward excursions of the Gulf Stream and the subpolar gyre in the Labrador Sea permit anomalously large volumes of Labrador water to pass the Tail of the Grand Bank and penetrate

westward along the continental slope at depths of 100-300m. As this flow encounters cross-shelf channels with sill depths greater than 100m, the anomalous Labrador Slope water passes onto the continental shelf, flooding the deeper basins. The lag between the NAO minimum and slope water penetration of the shelf is related to the time required for the slope water pulse to advect from the Tail of the Bank to the point in question. Such an event is documented for the NAO minimum recorded in the winter of 1995-'96, which caused the Labrador Slope Water to flood the deep basins of the Gulf of Maine in early 1998 (Drinkwater, *et al.*, 2002)

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SESSION 2. PRESENTATION 2

Long Range Active Sonar Performance (Sonar Equation, Propagation And Reverberation Considerations)

Sean P. Pecknold, John C. Osler, Dale D. Ellis
Defence Research and Development Canada — Atlantic, PO Box 1012, Dartmouth, NS, B2Y 3Z7. Email sean.pecknold@drdc-rddc.gc.ca

Active sonar performance can be evaluated using the active sonar equation. The signal excess, a determiner of the probability of detection of a target, depends on the sonar system being used, the nature and size of the target, and the ocean environment. The environment in turn determines the propagation, or transmission, loss of the sonar signal, and together with the signal type and strength, and the receiver characteristics, establishes the limits that noise or reverberation place upon signal excess.

Here, we model the propagation of a 1 kHz signal in the eastern Georges Bank and the central Bay of Fundy areas. Sound speed profiles are taken from mean monthly temperature and salinity climatological data, and used with range-dependent bathymetry and sediment types to calculate expected propagation losses out to a 40 km range in each environment for each season. In both areas, the sonar system is situated at mid-water column depth (40 m on Georges Bank and 100 m in the Bay of Fundy), with fish school target depths of 0 m, 40 m, and 80 m for the Georges Bank environment and 0 m, 50 m, 100 m, and 150 m for the Bay of Fundy environment. The modeled transmission loss shows little seasonal or azimuthal dependence in the Georges Bank environment, although the loss is depth dependent. The Bay of Fundy environment shows considerably more dependence on bearing, and in general, the

transmission loss in the Bay of Fundy is greater than that on Georges Bank: signal strength for the Bay of Fundy for a representative mid-column target falls off as approximately $18.6\log_{10}r$, while on Georges Bank the signal strength falls off as approximately $16.4\log_{10}r$.

Reverberation levels were also calculated for the environments, assuming a 96 element towed array receiver with a 1.8° beamwidth, and a dual free-flooding ring projector similar to that of the DRDC Atlantic VP2 emitting a 100 ms signal. The model results indicated that both environments should be reverberation limited for signal levels down to about 190 dB in fair weather. Therefore, down to this level, the signal excess would be independent of signal strength. Calculations of signal excess for both locations indicate that detection ranges for fish schools with target strengths 10 dB greater than detection threshold could be 15-20 km for the Bay of Fundy and twice that for Georges Bank. A further consideration is the issue of oceanographic variability. Studies on the sensitivity of propagation to sound speed variability done in other environments show that transmission loss changes caused by sound speed fluctuations can be significant in some cases and negligible in others.

SESSION 2. PRESENTATION 3

No abstract.

SESSION 2. PRESENTATION 4

Target Strength Issues in Conventional High Frequency Assessment of Herring

J. Michael Jech
NOAA-Fisheries, Northeast Fisheries Science Center, 166 Water. St., Woods Hole, MA, USA (michael.jech@noaa.gov)

Routine acoustical surveys for estimating Atlantic herring (*Clupea harengus*) population abundance have been conducted on Georges Bank during the autumn spawning season from 1998 to present (Overholtz et al. 2006). Acoustical data were collected with a Simrad EK500 scientific echo sounder operating 12- or 18-, 38-, and 120-kHz, and split-beam transducers. Biological measurements and verification of acoustical scatterers were obtained with a pelagic trawl. Allocation of acoustic backscatter to species is done by visually inspecting echograms, comparison to trawl catch data, and with objective classification algorithms (Jech and Michael, 2006). In 2006, we collected coordinated echosounder, biological, multibeam, and long-range sonar measurements on the northern edge of Georges Bank. Historic high-frequency and fish-resonance-frequency (Nero et al. 2004) acoustic and biological data were used to define the spatial extent of the herring distribution, localized "hot spots" of herring abundance, and a general timeframe for the herring spawning migration. The target strength of Atlantic herring in this region is being addressed by collecting live fish at sea and using a theoretical backscatter model (Kirchhoff-ray mode model) to predict target strength (Jech and Horne, 2002) and *in situ* target strength measurements. Verification of the backscattering model for other Clupeid species has been examined with controlled laboratory experiments (Reeder et al. 2004). Measured and predicted target strengths are beginning to be applied to survey data to improve accuracy in population estimates.

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SESSION 2. PRESENTATION 5

Low Frequency Acoustic Backscatter Characteristics of Targeted Fish and Fish Assemblages

Redwood W. Nero
Naval Research Laboratory, Stennis Space Center, MS
Present address: NMFS, Southeast Fisheries Science Center, Stennis Space Center, MS

An extensive collection of Naval Research Laboratory (NRL) direct path backscatter measurements from a wide variety of swimbladder bearing fish in different environments is used to demonstrate the consistent behavior and predictability of their low frequency resonance response. Love's formulation of the resonance (1978, JASA, 64:571-580) has proven very reliable in matching many measurements of volume reverberation to ancillary fisheries information on fish size, species and abundance. The model has also worked well when extended to tightly packed ensembles where resonant coupling and interference effects become important. From a stock's basic information on fish size and behavior, reasonable estimates can be made of the dominant frequency response and the likely utility of long range low frequency measurements. The model is applied to ancillary trawl data on fish stocks to help interpret the results of two recent experiments, one off the shelf of New Jersey and the other on the north flank of Georges Bank.

CV of Author
Ph.D. in Zoology, Univ. of Toronto, 1985
Postdoc with C. S. Clay and J. J. Magnuson 1986-1990
US Navy, Naval Research Laboratory 1990-2006 (16 years), measuring and predicting the low frequency scattering response from fish.
Recently transferred to NOAA's National Marine Fisheries Service, working on a variety of fisheries and environmental issues in the northern Gulf of Mexico.

SESSION 2. PRESENTATION 6

The ONR Five Octave Research Array (FORA) at Penn State

John Preston
Applied Research Laboratory, The Penn State Univ., P.O. Box 30, State College PA 16804

A towed/vertical array system has been built to support the ONR ocean acoustic program's 6.1 experimental research efforts. The array consists of both a linear section for standard beamforming and a cardioid section giving it port/starboard discrimination capabilities. The linear section is comprised of 4 modules with half wavelength hydrophone spacing corresponding to cutoff frequencies of 250, 500, 1000, and 2000 Hz. Each linear aperture is made up of 64 hydrophone channels with a total linear aperture length of 189 meters. The cardioid module consists of 78 hydrophone triplets arranged in an equilateral triangle with 38.5 mm spacing between the individual phones. The linear spacing between each triplet set is 0.2 meters for a cutoff frequency of 3750 Hz. In addition to the acoustic sensors, the array contains 3 non-acoustic sensor suites and an additional pressure sensor to provide real time array heading, pitch, roll, and depth along with temperature at various positions along the array. Array control for setting of sampling rates, array gain, and monitoring of both acoustic and non-acoustic data is provided by a standard PC. The array supports sampling rates from 6.25-25 kHz for the acoustic data with 24 bit A/D conversion. Array telemetry is ATM/SONET with a data rate of 155 Mb/s. The acquisition system acquires directly to SCSI ultra 320 disk and is based on a COTS Linux workstation. Since taking delivery in May 2002, the FORA has been deployed in five separate sea trials, including the recent Gulf of Maine experiment held Sept - Oct. 2006 near George's Bank in the Atlantic Ocean. Some preliminary results and data are presented from a 2003 trial illustrating array capabilities.

SESSION 2. PRESENTATION 7

Overview of the DRDC Towed Array and Source

Sean P. Pecknold, Dale D. Ellis
DRDC Atlantic, Dartmouth, Nova Scotia, Canada

The DRDC Towed Integrated Active Passive Sonar (TIAPS) consists of a "wet end" (acoustic source and towed array receiver) and "dry end" data processing system. TIAPS operates in conjunction with either a vertical or horizontal array towed source. The primary source is the VP2 consisting of two free-flooding ring projectors separated vertically, producing an omni-directional radiation pattern in the horizontal plane, with a vertical beam pattern having reduced intensity in the vertical to reduce bottom reverberation. Maximum levels are > 220 dB re 1 μPa at 1 m over the 900 Hz to 2 kHz frequency band. The VP2 source is towed by the same vessel but physically separate from the receive array. An alternate source, no longer in service, is a horizontal projector consisting of a 32 barrel-stave radiator array towed in-line as an integral part of the TIAPS array with usable frequency range 1 - 1.3 kHz. The receiver array components include the Digital Directional Acoustic Sensor Module (DASM), and Multi-Aperture Networked Towed Array (MANTArray). The DASM consists of 96 Combined Omni-Directional Resolved Sensor (CORDS) units (with omni and dipole elements, 192 channels total) allowing resolution of left-right ambiguity. The MANTArray consists of 256 channels comprising sub-arrays or modules of more conventional omnidirectional acoustic sensors. These include 2 modules of 1500 Hz cut-off frequency, 6 modules of 750 Hz cut-off, plus several lower frequency modules – the latter synthesized by sub-sampling elements of the higher frequency modules. All channels

of both the DASM and MANTArray are sampled to 24 bits at a rate of 4096 Hz. The broadside receive –3 dB beamwidth with Hann weighting is 1.7 degrees. The total array length is 1.7 km including the forward end 600 m VIM (vibration isolation module) and tow cable. The dry end consists of the STB (System Test Bed), which performs real-time beamforming and signal processing, along with display of towed array, sonobuoy and non-acoustic (e.g., radar) results. The raw acoustic data is stored for future processing and scientific analysis.

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SESSION 3. PRESENTATION 1

No abstract.

SESSION 3. PRESENTATION 2

Effects of Low Frequency Anthropogenic Sounds on Marine Mammals

Jack Lawson
DFO, Newfoundland and Labrador Region, NAFC, P.O. Box 5669, St. John's, NL A1C 5X1

Low frequency anthropogenic sounds may be a significant issue for marine mammals since auditory and non-auditory physiological effects or injuries could occur in animals exposed to strong underwater sounds, and range along a continuum: masking of acoustic activities, such as social communication and foraging; behavioural disruption; temporary or permanent hearing threshold shift; injury and/or death due to direct or indirect severe injury; population-level effects.

The nature of low frequency sound impacts on marine mammals, if any, are variable both because of behavioural variation in these long-lived and intelligent animals, and in their physical characteristics. There will be differences in hearing sensitivity and dynamic hearing range among species based on laboratory studies and extrapolation from what we know about their physical characteristics. We could broadly subdivide marine mammals into infrasonic baleen whales, sonic to high frequency species (e.g., northern bottlenose whales, most seals), and ultrasonic-dominant species (e.g., harbour porpoises).

Modelling acoustic energy exposure from a source, especially if it is moving, is a complex task and yields a high degree of uncertainty in the prediction of anthropogenic impacts. A precautionary approach to management is required if modelling results are used to inform decisions, and baseline research is critical. In the case of low frequency activity sonars, regulators should take care in monitoring and mitigation, assume worst-case exposures and responses, conduct baseline studies before and after onset of sonar activity, and for some areas (e.g., Sable Gully, Bay of Fundy) perhaps prohibit low frequency sonar use. Projecting population-level consequences of acoustic exposure is an even more convoluted process.

Ways to mitigate effects of anthropogenic sources producing intense low frequency sound could include operational procedures such as (1) determination (acoustically, visually, previous information) of species in the area, (2) ramp-up of the source level, and (3) decrease source level or shut down equipment when marine mammals enter a pre-determined "safety zone". Evidence that sonar sounds can, in special circumstances, lead directly (e.g., injury) or indirectly (e.g., stranding, changes in hearing), to marine mammal mortality suggests caution is warranted, and safety zones may need to be larger than distances needed to prevent hearing loss for some species (particularly beaked whales), and in some areas.

SESSION 3. PRESENTATION 3

Effects of Low Frequency Sound on Fish

Svein Løkkeborg
Institute of Marine Research, P.O. Box 1870 Nordnes, N-5817 Bergen, Norway

The presentation provided a short overview of how fish use sound, the hearing abilities in fish and how fish respond to anthropogenic sound. A review of field studies carried out to investigate effects of seismic survey activities on fish behaviour, fish distribution and commercial catch rates was given. Three studies on effects of sound on herring were also reviewed.

Fish may use sound to localise prey by listening for sound produced by prey or feeding sound produced by conspecifics. Sound may also be important to detect and avoid predators. Thirdly, some fish species, e.g. haddock (*Melanogrammus aeglefinus*), make sound that is important for mating and breeding activities. Thus hearing sounds is important to maximise foraging (i.e. growth), survival and reproduction in many species of fish, and therefore critical for three vital activities of an animal's life.

In terms of their hearing abilities, fishes are group into two categories. Species with an accessory link between the swimbladder and the inner ear are called hearing specialists whereas species without this pathway to the ear are called non-specialists or generalists. The specialists generally have a lower hearing threshold and are sensitive to a wider frequency range. This means that hearing specialists, such as herring (*Clupea harengus*) for example, are sensitive to sound produced by low-frequency sonars, whereas most generalists are unlikely to respond to these frequencies.

Fish have been shown to respond to anthropogenic sound by exhibiting startle, alarm or avoidance responses. A startle response (also called C-start response) is a stereotyped response in which the fish's body forms a C-shape that points it away from the sound source. The C-start response often occurs following brief loud noises with a rapid rise time and may initiate an avoidance reaction away from a noxious source. Alarm responses may involve milling, changes in schooling behaviour or increased swimming activity. Fish may avoid areas of increased sound levels by moving horizontally or vertically away from the sound source.

Observations of gadoids (cod (*Gadus morhua*), pollack (*Pollachius pollachius*), saithe (*P. virens*) and whiting (*Merlangius merlangus*)) on an inshore reef using TV camera and acoustic tags have been made during air-gun firing (Wardle et al. 2001). All fish observed showed a C-start response at all ranges tested, with the maximum range being 109 m giving a sound level of 195 dB at the reef. The movement pattern of the fish was slightly changed, but no movement of fish away from the gun or the reef was observed. The authors suggested that the air-gun shot

on its own is either too complicated or too short to give directional information to allow the fish to respond with directed movements away from the sound source. Furthermore, a resident fish population inhabiting a reef may show strong site-fidelity, whereas fish in open sea may respond more freely to stimuli presented by seismic activities.

Detailed field observations of behavioural changes in rockfish (*Sebastes spp.*) exposed to air-gun sounds have been made by Pearson et al. (1992). Fish held in a field enclosure showed changes in both swimming pattern and depth distribution during 10-min exposures to sounds from a single air gun. These observations suggested that subtle changes in behaviour (changes in depth distribution and shifts to active behaviours such as eddying and milling) to sounds became evident at 161 dB, and that changes in these behaviours became more extensive as sound level increased. The threshold for alarm responses (increases in activity and changes in schooling and water position) was observed at about 180 dB, and the threshold for startle responses appeared to be between 200 and 205 dB. Differences in response patterns were observed between the five species of rockfish studied, i.e. the character of the alarm response, the threshold for the startle response and whether they responded individually or as a school.

Skalski et al. (1992) examined how single air gun emission affected catchability in the rockfish hook-and-line fishery along the California coast. A survey vessel traversed over fish aggregations on rock pinnacles at 82 – 183 m depth and produced sound levels of 186 - 191 dB at the base of rockfish aggregations. There was an average decline in total catch rates of 52% under sound emissions. There was no sign of fish dispersing from the pinnacles, and the reduced catchability was explained by decreased responsiveness to baits and behavioural changes as fish schools were observed to descend in the water column. This finding is in agreement with that of Wardle et al. (2001) indicating that fish associated with underwater structures tend to be more stationary and are less likely to disperse under emission conditions than fish located at featureless banks.

Engås et al. (1996) investigated spatial and temporal extent of the effects of seismic survey activities on local fish abundance and commercial catch rates. Continuous seismic shooting using an 18-gun array was conducted over a 5-day period within an area of 3 x 10 nautical miles (nmi). Trawl catches of cod and haddock and longline catches of haddock in an area of 40 x 40 nmi centred around the shooting area declined by about 50% during the shooting period compared to a 7-day pre-shooting period. The catch reductions were most pronounced within the shooting area where trawl catches of both species and longline catches of haddock decreased by about 70% and longline catches of cod by 45%. Except for the longline catches of cod, catch rates declined over an area of 18 nmi from the seismic shooting area and there was no sign of increases in catch rates during a 5-day period after shooting ended. The local abundances of cod and haddock in the experimental area were estimated from acoustic mapping and found to decline in accordance with the catch reductions.

Behavioural responses to a variety of sounds were studied in net-penned Pacific herring (*Clupea harengus pallasi*) (Schwarz and Greer 1984). Herring did not respond to high frequency sonar or echo sounders or to tape-recorded sounds of natural origin such as vocalizations by gulls, killer whales and sea lions. Avoidance responses were elicited by sounds of approaching vessels and by different combinations of amplitude, frequency and temporal pattern of synthesized sounds. Alarm and occasionally startle responses were elicited by synthesized sounds with a rapid rise time.

Jørgensen et al. (2005) studied responses of fishes to mid-frequency sonars (1.6 and 4 kHz) and observed increased swimming activity in juvenile herring exposed to sonar signals around 160 dB. Juvenile herring exhibited startle responses to signals around 170 dB, and these

responses were followed by abnormal swimming at higher received levels (180-190 dB). Interestingly, no responses to sonar sound were observed in three "hearing generalist species" (cod, saithe, wolffish (*Anarhichas minor*)).

The distribution and abundance of herring were mapped acoustically within a seismic survey area off the Norwegian west coast (Slotte et al. 2004). Three acoustic surveys were carried out, and in all survey the acoustic abundance of herring was lower within the seismic shooting area, with increasing abundance to a distance of about 20 nmi from the centre of the shooting area.

In conclusion, fishes are shown to be affected by low frequency sounds, and hearing specialists such as herring respond to a wider range of frequencies the hearing generalists. Avoidance responses are the most pronounced and likely responses to human-generated sounds of low frequency. Such responses have been shown to affect commercial catch rates, and may also cause movements away from feeding and spawning grounds.

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SESSION 3. PRESENTATION 4

No abstract.

OBSERVATIONS AND CONCLUSIONS

The objectives of this section are to review the relevant information on low frequency sonar for long range fish detection – for which the workshop itself has the main vehicle, to draw conclusions regarding the technology's application, and to make recommendations regarding future directions in DFO Maritimes Region. The principal conclusion is that detection of extended pelagic fish aggregations to ranges of 20 – 30 km using towed array active sonar operating in the sub-kilohertz to low kilohertz frequency range (i.e., OAWRS) appears both feasible and demonstrated. Low frequency towed-array sonar technology was successfully used to detect and map wide-area distributions of herring on Georges Bank in the fall 2006 (Session 1, Presentation 2). This quantitative detection experiment was supported and verified by both conventional beam echosounding and by trawl sampling.

While the current leading proponents of OAWRS are confident that these techniques can achieve a high degree of stand-alone quantitative accuracy, the DFO convenors maintain a more conservative view: achieving *stand-alone* biomass quantification to anything approaching the 10 – 20% absolute accuracy normally demanded by assessment biologists would appear rather optimistic. Conventional vertical dual and split-beam scientific echosounding presently struggles to achieve such accuracies. For long range sonar the number of determinative variables are inherently larger and many would appear more difficult to accurately assess. On the positive side, long range sonar, even at its present state of development, would be advantageous when applied *synergistically* with conventional echosounding and trawl sampling, allowing the latter techniques to be applied with greater efficiency (survey cost savings) and reliability. Long range sonar technology could be used to search broad areas of the ocean for

fish aggregations and to better understand the dynamic behaviour of spawning pelagic fishes. Quantitative applications might best be approached by using long range sonar to spatially/temporally extrapolate well chosen vertical beam echosounder quantifications.

A Canadian *hardware* capability for detecting pelagic fish schools to ranges of at least 20 km using the DRDC - Atlantic TIAPS system was assessed, supported by a detailed theoretical analysis conducted by DRDC - Atlantic for two representative eastern Canadian sites, one on northern Georges Bank and the other at the mouth of the Bay of Fundy (Session 2, Presentation 2). To make TIAPS an efficient operational system for real-time fisheries applications would require adaptation or replacement of the current military-oriented presentation and display algorithms. Interfacing with the MIT display software may be a practical solution for the current limitations. The fish-related hardware capability remains to be verified by field experiment.

Acoustic propagation effects must be carefully considered both in the design of field experiments at multi-kilometer ranges and in the quantitative interpretation of sonar fish backscatter sonar levels and imagery. Methodologies exist and have been applied in past studies (Session 1, Presentations 1 and 2). Acoustic propagation predictions should be adequately supported by concurrently sampled sound speed profiles (or TS profiles from which sound speed can be derived) as the physical properties of both the Gulf of Maine and bordering Nova Scotia waters are subject to strong inter-annular, as well as seasonal variability (Session 2, Presentation 1) which affect acoustic propagation. Strong spatial gradients of oceanographic properties or frontal zones are also expected on approaching inshore or shallow water areas where the water column is homogenized by tidal mixing.

Low frequency towed-array sonars have some inherent downsides: (1) they constitute an expensive capital investment (perhaps >$1M even using arrays of existing design apart from the acoustic source) and require periodic maintenance (approximately $50K per season as pointed out in Session 2, Presentation 6); and (2) environmental concerns surround high LF acoustic source levels. LF active sonar sources often radiate omni-directionally in the horizontal plane resulting in large surrounding areas of significant ensonification. Herring spawning areas in western Nova Scotia, the likely target area for future LF survey, are also near the summer and fall habitat of the endangered northern right whale whose hearing may be especially sensitive to LF sound.

Medium frequency sonar systems offer lower cost alternatives (a factor of 5 - 10) to LF towed-array sonars (Session 1, Presentations 4 and 5). Increased chemical absorption in the ocean limits these systems to detection ranges somewhere between those achievable using LF towed arrays and those using traditional high frequency vessel-based fishery multibeam sonars. The medium frequency systems described, unlike shipboard multibeams but like LF towed arrays, can be lowered to, or towed, at the optimal operational depths dictated by propagation considerations.

The single beam sidescan geometry (Session 1, Presentation 4) has the technical advantage of achieving high directivity in matched transmit and receive patterns, thereby, to a degree, offsetting the increased acoustic absorption compared to LF systems. The specific sidescan was developed and maintained at a DFO facility. The associated hardware maintenance, field deployment, and signal processing capabilities can be better accommodated "in-house" than for LF arrays – and the system currently resides within DFO. Use of medium acoustic frequencies and a narrow transmit beam in the horizontal plane may also leave a lower environment footprint. The critical disadvantage of sidescans is the loss of true synoptic view – although a long lateral range sidescan survey will normally constitute a closer approximation to a synoptic

"snapshot" than a conventional vertical beam echosounder survey covering the identical area. Also lost with medium frequency systems is the inherent ability to exploit LF fish swimbladder resonances used to identify species, size, and/or depth (Session 2, Presentations 4 and 5).

Low frequency forward scatter systems were not explored during the workshop due to the absence of a leading proponent. This option was later examined in a seminar and technical meeting reported in Appendix 4. The forward scatter "Bioacoustic Absorption Spectroscopy" (BAS) technique offers some potential advantages over long range LF backscatter sonars. These include: (1) much lower transmit levels which both reduce the environmental footprint and enable long-term stand-alone moored deployments; (2) practical operation over a very wide range of closely spaced frequencies, which potentially enables species and length class discernment by bracketing the swimbladder frequencies of all species present (Note: Backscatter systems, in theory, can also do this but for technical and operational reasons this is much more difficult to achieve in practice); (3) BAS can yield averaged information about the depth distribution of fish, not generally possible with horizontal receive array backscatter systems; and (4) BAS systems are, reportedly, sensitive to fish distributed near–surface and near-bottom, regions often difficult to "see" or properly interpret with conventional sonar (Session 1, Presentation 3).

BAS forward scatter systems appear capable of a degree of quantification. For fisheries applications, BAS can only supply synoptic estimates along a single, or, at best, a very limited number, of fixed lines. Integration to obtain total biomass over an extended area, the primary objective of stock assessment, would appear to be a tedious process even if system components were reasonably portable. Nevertheless, integration may be possible in a restricted area such as German Bank with careful experiment design. While there is the theoretical capability of discerning size and hence year-class information from BAS it is presently not certain - but possible - that the resolutions achievable would be useful as applied to Maritimes Region herring. BAS quantification is also critically sensitive to bottom and sub-bottom acoustic properties which are best defined by alternative survey techniques.

The main downside to a BAS survey is the lack of a spatial imaging capability. Consequently, such systems would have no utility for strategically directing concurrent conventional surveys neither for aggregating and migrating fish species like herring nor for studying their aggregation behaviour or systematic movements. Lack of detailed information on aggregation and movement could also severely impact biomass quantification.

In summary, it is the opinion of the DFO convenors that low frequency towed-array active sonar should receive the highest priority among the techniques reviewed for investigating the wide-area distribution and abundance of pelagic fishes in DFO Maritimes Region. Although these systems will be very costly to field and, if existing Canadian sonar hardware (TIAPS) is utilized, would require potentially expensive associated software modification/development, the technology offers the only true broad-scale synoptic view of the pelagic environment. Costs might possibly be mitigated, at least in the early stages of development, if a demonstration field experiment can be undertaken as a multi-institutional joint venture where the partners pursue relevant parallel objectives. As alluded to previously, an attractive possibility would be using TIAPS with the existing MIT real-time display and post processing software, an avenue currently being further explored. The forward scatter LF BAS and medium frequency systems also appear to have real, but more limited and/or specialized applications.

Finally, it should be emphasized that while both long range acoustic backscatter sonars and forward scatter systems offer intriguing potentials for stock assessment applications, both techniques are currently in their formative stages, and both are very much in need of carefully

controlled field demonstration experiments before being considered useful quantitative tools. DFO exploitation of the capabilities of these techniques would necessarily involve conducting the required field trials as a proof of concept. A unique opportunity is currently perceived for DFO to move forward with cutting-edge science, supported by strong collaborations, and the local Government of Canada availability of much necessary acoustic hardware and specialized acoustic expertise.

The above comments and recommendations are entirely the conclusions of the DFO convenors and should not be construed as necessarily reflecting any workshop consensus or the wider view of, or defining any future policy or direction of, the Department of Fisheries and Oceans.

ACKNOWLEDGEMENTS

The DFO convenors wish to extend their sincere thanks to all invited workshop participants who have contributed time and energy toward making this venture a most informative and successful gathering. Several people deserve special credit: Dale Ellis and Jim Theriault of DRDC – Atlantic, who volunteered to serve on our Workshop Organizing Committee, were of great assistance in advising about specialized areas of acoustics, as well as facilitating contracts within the wider defence acoustics community locally and abroad. Mark Trevorrow, also of DRDC – Atlantic, did a masterful job in filling in for the originally scheduled Introductory Speaker at very short notice. Finally we would like to acknowledge DFO Administrative Officers Michele Saunders, at St. Andrews Biological Station, and Helen Dussault, at BIO, who capably guided us though proper bureaucratic procedures in arranging this workshop and, in addition, handled the details of foreign travel and expense claims – a far from minor task.

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APPENDICES

Appendix 1. Workshop Agenda

Subject: The potential application of long range, low frequency sonar to quantitative fisheries assessment and environmental surveying with focus on DFO Maritimes Region.

Monday January 29, 2007

Preliminary Session

13:00 – 13:30 Opening Remarks - Gary Melvin, DFO/SABS
Welcome – Michael Sinclair, Regional Director, (DFO) Science Branch
Statement of Workshop Objectives - Norman Cochrane, DFO/BIO

13:30 – 14:15 Introductory Speakers – Mark V. Trevorrow, DRDC Atlantic and Norman Cochrane, DFO/BIO
An introduction to long range sonar, and its application in the detection of biological targets.

14:15 – 14:45 Issues in surveying pelagic fishes potentially amenable to long range sonar: Atlantic herring as study case – Gary Melvin, DFO/SABS

14:45 – 15:00 Health Break (Coffee, juice, snacks available)

Session 1. Long Range Acoustic Fish Detection
Chairman: Norman Cochrane, DFO/BIO

15:00 – 15:45 Principal Scientific Address: Fish population and behaviour revealed by instantaneous Continental Shelf-scale imaging - Nicholas C. Makris, MIT; Purnima Ratilal, Northeastern Univ.; Deanelle Symonds, Srinivasan Jagannathan, Sunwoong Lee, MIT; and Redwood W. Nero, NRL Stennis Space Center [Presented by Nicholas Makris]

15:45 – 16:15 Presentation 2: Spatial and temporal behaviour of Atlantic herring spawning on Georges Bank revealed by Ocean Acoustics Waveguide Remote Sensing – Purnima Ratilal, Northeastern Univ.

19:00 Evening Meal for participants – McKelvie's, 1680 Lower Water Street, Halifax

Tuesday January 30, 2007

Session 1 (continued)

09:00 – 09:30 Presentation 3: Examples from active sonar trials of direct-path and convergence zone scattering off fish – Roger C. Gauss, NRL Washington [Presented by Woody Nero, NOAA, former NRL]

09:30 – 10:00 Presentation 4: Intermediate range fish detection with a 12 kHz sidescan sonar - Mark V. Trevorrow, DRDC Atlantic

10:00 – 10:15 Health Break (Coffee, juice, snacks available)

10:15 – 11:00 Presentation 5: Development of mid-frequency multibeam sonar for fisheries applications – John K. Horne, Christopher D. Jones, and Michael Wolfson, Univ. of Washington [Presented by John Horne]

11:00 – 11:30 General discussion on long range acoustic fish detection

Session 2. Long Range Active Sonar Detection and Quantification of Fish
Chairman: Dale D. Ellis, DRDC Atlantic

11:30 – 12:00 Presentation 1: An overview of oceanographic conditions in the Gulf of Maine/Bay of Fundy - Peter C. Smith, DFO/ BIO.

12:00 – 13:00 Lunch

13:00 – 13:45 Presentation 2: Long range active sonar performance (Sonar equation, propagation and reverberation considerations) - Sean P. Pecknold, John C. Osler, and Dale D. Ellis, DRDC Atlantic [Presented by John Osler]

13:45 – 14:15 Presentation 3: Ambient noise background in coastal waters of Eastern Canada - Francine Desharnais, DRDC Atlantic

14:15 – 14:45 Presentation 4: Target strength issues in conventional high frequency assessment of herring – Michael Jech, NOAA NEFSC

14:45 – 15:15 Presentation 5: Low frequency acoustic backscatter characteristics of targeted fish and fish assemblages - Woody Nero, NOAA (former NRL)

15:15 – 15:30 Health Break (Coffee, juice, snacks available)

15:30 – 16:00 Presentation 6: The ONR Five Octave Research Array (FORA) at Penn State – John Preston, Applied Research Lab, The Penn State Univ.

16:00 – 16:10 Presentation 7: Overview of the DRDC towed array and source - Sean P. Pecknold and Dale D. Ellis, DRDC Atlantic [Presented by Chairman Dale Ellis].

16:10 – 17:00 General discussion: Long range sonar technology for fish detection.

Wednesday January 31, 2007

Session 3. Environmental Considerations
Chairman: Gary Melvin, DFO/SABS

09:00 – 09:30 Presentation 1: Spatial and temporal distribution of marine mammals in Southwest Nova Scotia/ Bay of Fundy region – Kent Smedbol, DFO/SABS

09:30 – 10:00 Presentation 2: Effects of low frequency anthropogenic sounds on marine mammals – Jack Lawson, DFO/NWAFC

10:00 – 10:15 Health Break (Coffee, juice, snacks available)

10:15 – 10:45 Presentation 3: Effects of low frequency sound on fish – Svein Løkkeborg, IMR, Bergen

10:45 – 11:15 Presentation 4: Sonar R&D risk management: Potential impact on marine mammals – Jim Theriault, DRDC - Atlantic [Presented by Francine Desharnais]

Session 4. Exploratory General Discussion

11:15 – 13:00 Discussion: Where do we go from here?
13:00 Close

Editors' note: The above represents the workshop Agenda as delivered and incorporates some late changes in titles and authorship.

Appendix 2. Workshop Organizing Committee

This DFO sponsored workshop was organized with assistance from Defence Research and Development Canada – Atlantic.

Organizing Committee

Norman A. Cochrane
Department of Fisheries and Oceans
Bedford Institute of Oceanography
Tel. (902) 426-5172, e-mail: CochraneN@mar.dfo-mpo.gc.ca

Dale D. Ellis
Defence Research and Development Canada – Atlantic
Tel. (902) 426-3100 Ext. 104, e-mail: Dale.Ellis@drdc-rddc.gc.ca

Gary D. Melvin
Department of Fisheries and Oceans
Saint Andrew Biological Station
Tel. (506) 529-5874, e-mail: MelvinG@mar.dfo-mpo.gc.ca

James A. Theriault (Jim)
Defence Research and Development Canada – Atlantic
Tel. (902) 426-3100 Ext. 376, e-mail: Jim.Theriault@drdc-rddc.gc.ca

Appendix 3. Workshop Attendees

Scientific Participants

Bain, Hugh
Environment and Biodiversity Science Branch
Ecosystem Science Directorate
DFO/NHQ Ottawa
Tel. (613) 990-0283, e-mail: BainH@dfo-mpo.gc.ca

Cochrane, Norman A.
Ocean Sciences Division, DFO/BIO
Tel. (902) 426-5172, e-mail: CochraneN@mar.dfo-mpo.gc.ca

Desharnais, Francine
DND/DRDC - Atlantic
Tel. (902) 426-3100 Ext. 219, e-mail: francine.desharnais@drdc-rddc.gc.ca

Eisner, Richard
Manager, Innovation Office
DFO/BIO
Tel. (902) 426-7564, e-mail: EisnerR@mar.dfo-mpo.gc.ca

Ellis, Dale D.
DND/DRDC - Atlantic
Tel. (902) 426-3100 Ext. 104, e-mail: Dale.Ellis@drdc-rddc.gc.ca

Horne, John K.
University of Washington
Tel. (206) 221-6890, e-mail: jhorne@u.washington.edu

Jech, Michael (Mike)
NOAA/NMFS/NFSC Woods Hole
Tel: (508) 495-2353, e-mail: Michael.Jech@noaa.gov

Lawson, John W. (Jack)
DFO/NWAFC
Tel. (709) 772-2285, e-mail: LawsonJ@dfo-mpo.gc.ca

Lokkeborg, Svein
Institute of Marine Research, Bergen
Tel. +47 55236826, e-mail: sveinl@imr.no

Macnab, Paul
Oceans and Coastal Management Division, DFO/BIO
Tel. (902) 426-6391, e-mail: MacnabP@mar.dfo-mpo.gc.ca

Makris, Nicholas C. (Nick)
Department of Mechanical Engineering, MIT
Tel.: (617) 253-2350, e-mail: makris@mit.edu

Mayer, Larry, Director
Center for Coastal and Ocean Mapping, UNH
Tel. (603) 862-2615, e-mail: larry@ccom.unh.edu

McQuinn, Ian
DFO/IML
Tel. (418) 775-0627, e-mail : Mcquinni@dfo-mpo.gc.ca

Melvin, Gary D.
DFO/SABS
Tel. (506) 529-5874, e-mail: MelvinG@mar.dfo-mpo.gc.ca

Millar, David
Oceans and Coastal Management Division, DFO/BIO
Tel. (902) 426-9926, e-mail: MillarDC@mar.dfo-mpo.gc.ca

Nero, Redwood W. (Woody)
NOAA/SEFSC
Tel: (228) 688-3138, e-mail: woody.nero@noaa.gov

Osler, John
DND/DRDC - Atlantic
Tel. (902) 426-3100 Ext. 199, e-mail: John.Osler@drdc-rddc.gc.ca

Preston, John R.
ARL/Penn. State Univ.
Tel. (814) 863-1310, e-mail: preston@ciao.arl.psu.edu

Ratilal, Purnima
Department of Electrical and Computer Engineering
Northeastern University
Tel. (617) 373-8458, e-mail: purnima@ece.neu.edu

Sinclair, Michael M.
Regional Director, Science Branch, DFO/BIO
Tel. (902) 426-3490, e-mail: SinclairM@mar.dfo-mpo.gc.ca

Smedbol, Kent R.
DFO/SABS
Tel. (506) 529-5976, e-mail: SmedbolK@mar.dfo-mpo.gc.ca

Smith, Peter C.
Manager, Ocean Sciences Division, DFO/BIO
(Address as above)
Tel. (902) 426-3474, e-mail: SmithPC@mar.dfo-mpo.gc.ca

Sponagle, Neil
Section Head of Underwater Sensing
DND/DRDC - Atlantic
Tel. (902) 426-3100 Ext. 199, e-mail: Neil.Sponagle@drdc-rddc.gc.ca

Trevorrow, Mark
DND/DRDC - Atlantic
Tel. (902) 426-3100 Ext. 315, e-mail: Mark.Trevorrow@drdc-rddc.gc.ca

Administrative Assistance

Saunders, Michele E.
Section Head Administrative Officer, DFO/SABS
Tel. (506) 529-5835, e-mail: SaundersME@mar.dfo-mpo.gc.ca

Appendix 4. Supplementary Seminar

Orest Diachok, an originally invited workshop presenter, was unfortunately unable to attend. Because of the relevance of his research to the themes of this workshop, Dr. Diachok was invited by the workshop convenors to present an alternative seminar at the Bedford Institute of Oceanography on February 23rd, 2007. The following is a running summary of his presentation titled "Bioacoustic Absorption Spectroscopy".

It was explained that Bioacoustic Absorption Spectroscopy (BAS) is a low frequency (0.3 - 7 kHz) forward scatter technique for discerning the characteristics of dispersed fishes or fish aggregations by measuring the magnitude and frequency dependence of the bioacoustic absorption coefficient over path lengths of typically 10 km. The roots of the technique extend back to long range acoustic absorption measurements made in the 1960's by David Weston and co-workers in the Bristol Channel.

BAS has several potential advantages over active sonar/echosounder backscatter measurements of fish concentrations:

1) Low source levels can be employed (~170 dB re 1μPa @ 1m versus typically >200 dB for active sonar).

2) Long measurement ranges from the acoustic source and any attending surface platform can be easily achieved with the consequence that quantitative abundance estimates are not subject to observation platform avoidance or behavioural modification as frequently the case for ship-based high frequency sonars/echosounders.

3) Absorption measurements are not sensitive to fish concentration close to the bottom. Backscatter based acoustic systems often have difficulty discerning fish in close proximity to the bottom.

4) Measurements can be more readily made over a wide range of closely spaced acoustic frequencies than with high power, highly directive backscatter systems. The resultant high frequency resolution may enable discernment of fish size distributions - and size-delineated year classes - from the absorption spectrum.

BAS does have some disadvantages:

1) The technique is inherently bistatic, requiring considerable separation between the source and receiver. Therefore, measurements cannot be conducted from a single platform. The need for multiple ships or moorings increases assessment costs.

2) Proper data inversion requires accurate knowledge of the sound speed structure within the water column as well as the acoustic properties of the bottom and sub-bottom.

The speaker proceeded to discuss the physical and mathematical basis of the technique in some detail.

Bioacoustic absorption from fish is largely determined by the acoustic properties of the fish swimbladder. Near resonance, swimbladders absorb incident sound; re-radiating the same nearly omni-directionally resulting in a pronounced dip in the spectrum of received forward propagating sound. The resonance response and attendant absorption cross section can be theoretically modelled. The resonance frequency is very dependent on swimbladder volume,

which by Boyle's Law is inversely proportional to ambient pressure and therefore related to fish depth. If fish are aggregated above a certain critical density, especially one implying less than one half acoustic wavelength physical separations, the swimbladders respond collectively making them appear acoustically larger and thus resonating at a lower frequency than for isolated population individuals.

A 2002 experiment in the Santa Barbara Channel was described which used an ultra-broadband (64 discrete frequencies between 0.3 and 10 kHz) 170 dB source. A moored vertical receiving arrays was deployed at about 4 km range in approximate 65 m of water Stepped frequency CW pulses from 0.5 to 10 s duration were transmitted. The source consisted of a moored barrel stave transducer for low frequencies and a ring transducer for the higher frequencies. The 290 lb source unit was battery powered with an operational endurance of about 2 days (initial fabrication cost approximately $300K; a copy would cost about $130K). The employed 16 element vertical receive array was of 45 m in length, the bottom end starting about 8 m above bottom. The recording units sat on bottom and could be acoustically released for recovery.

Some experimental results were shown for the same experiment. Resonant absorption lines from resident sardine and anchovy populations could be discerned. Night time vertical echosounder measurements showed a fish layer at about 13 m depth which shallow trawling showed to consist of 15 cm long sardines, 10 cm anchovies and 6 cm juvenile anchovies. The observation of three pronounced bioacoustic absorption peaks in experimental depth vs. frequency plots were in good agreement with theoretical expectations.

If precise inversion of field data to fish depths and densities is required, multi-parameter algorithms can be applied. Good knowledge of both the water column and bottom acoustic properties is highly advantageous for application of such algorithms. Some deficiencies in knowledge of the physical environment can be accommodated by making these adjustable parameters during inversion. Repeat absorption measurements made when the stock of interest is known to be present and absent can also constrain invariant environmental variables.

It is likely that BAS techniques could be applied to herring stocks off southwestern Nova Scotia – at least within limited fixed geographic areas. Current measurement systems would best be redesigned for longer endurance. A long term experiment (~1 month) could look at systematic changes in number densities and size related year classes and perhaps physiological state as compression of the swimbladder from expanded gonads may be relieved at the time of spawning.

In post-seminar discussions, it was conjectured that measurements of herring stock density over a given area of tens of kilometers extent might be possible by mooring a receive array at the center of the area and conducting a number of shallow source deployments from a vessel travelling around the periphery of the area. To obtain a useful degree of synopticity, these measurements would best be made during a single period of darkness (~8 hours) while herring are dispersed. Measurements over a prolonged period are expected to reveal migration patterns.